BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering
and Communication

BACHELOR'S THESIS

Brno, 2019

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BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF TELECOMMUNICATIONS

ÚSTAV TELEKOMUNIKACÍ

NEW TRENDS IN FIBRE OPTIC SOMMUNICATIONS

NOVÉ TRENDY V OPTICKÝCH VLÁKNOVÝCH KOMUNIKACÍCH

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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BRNO 2019

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní obor **Teleinformatika**
Ústav telekomunikací

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Ročník: 3 ***Akademický rok:*** 2018/19

NÁZEV TÉMATU:

Nové trendy v optických vláknových komunikacích

POKYNY PRO VYPRACOVÁNÍ:

Cílem bakalářské práce je teoretický rozbor problematiky přenosu informací optickým vláknem. Důraz bude kladen na nové trendy v optických komunikacích, především pak na nové typy optických vláken (MCF, FMF, apod.), modulačních formátů apod. Na základě teoretického rozboru budou provedeny návrh a simulace datového přenosu demonstrující vybraný typ moderní technologie. Na základě dosažených výsledků bude provedeno srovnání s aktuálním stavem.

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Termín zadání: 1.2.2019 ***Termín odevzdání:*** 27.5.2019

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předseda oborové rady

ABSTRACT

Optical fiber transmission is one of the leading methods of information transfer for long distance transmission. Various modulation formats have been developed to maximize information transferred through a communication channel. Such formats range from those that transfer one bit per symbol (such as Binary Phase Shift Keying, BPSK), or more such as Quadrature Phase Shift Keying, Dual Polarization Quadrature Phase Shift Keying and many other modulations. The goal of this thesis is to create and implement a 100 Gbps transmission system using DP QPSK modulation format. The results are descussed with respect to what was successfully implemented and improvements that can still be made to enhance the transmission distance and reduce BER among others. The simulation software used is PHOTOSS.

KEYWORDS

Optical fiber, Single mode, Multi Mode, Multi-core Fibre (MCF), Few Mode Fiber (FMF), Quadrature Phase Shift Keying (QPSK), Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), PHOTOSS, Dual Polarization QPSK (DP QPSK), Binary Phase Shift Keying (BPSK), Modes of lights, The Ray Model, Wave Model, Optical Transmitters and Receivers, Propagation of light in optical fibers, Geometric Optics, Polarization of light, Linear Polarization, Modes used in waveguides, Different standards of optical fibers, ITU recommendations, signal loss in optical fiber, crosstalk, eye opening, nonlinear effects, Self-Phase Modulation (SPM), Cross-Phase Modulation, Four-Wave Mixing, Nonlinear Scattering, Stimulated Brillouin Scatterig (SBS), Stimulated Raman Scatterring (SRS), Quantum Key Distribution (QKD).

ABSTRAKT

Přenos optických vláken je jednou z hlavních metod přenosu informací pro přenos na velké vzdálenosti. Byly vyvinuty různé modulační formáty pro maximalizaci informací přenášených prostřednictvím komunikačního kanálu. Takové formáty sahají od formátů, které přenášejí jeden bit na symbol (jako je například binární fázové posunování klíčů, BPSK), a nebo vice, jako je například Kvadraturní fázové posunovací klíčování, duální polarizační kvadraturní fázové řazení a mnoho dalších ostatní modulace. Cílem diplomové práce je vytvořit a implementovat přenosový systém s rychlostí 100 Gbps pomocí modulace formátu DP QPSK. Výsledky jsou shrnuty s ohledem na to, co bylo úspěšně implementováno, a zlepšení, která mohou být ještě učiněna pro zvýšení přenosové vzdálenosti a snížení BER mimo jiné. Použitý simulační software je PHOTOSS.

KLÍČOVÁ SLOVA

Optické vlákno, Single Mode Fiber (SMF), Multi Mode Fiber (MMF), Multi-Core Fibre (MCF), Few Mode Fiber (FMF), Kvadraturní fázové posunutí klíčů (QPSK), Klíčování posunu amplitudy (ASK), Klíče posunu frekvence (FSK), PHOTOSS, Duální polarizace QPSK (DP QPSK), Binary Phase Shift Keying (BPSK), Modely světel, Rayův model, vlnový model, optické vysílače a přijímače, šíření světla v optických vláknech, geometrická optika, polarizace světla, lineární polarizace, režimy používané ve vlnovodech, různé standardy optických vláken, doporučení ITU, ztráta signálu v optickém vlákně, přeslechy, otevírání očí, nelineární efekty, samofázová modulace (SPM), modulace mezi fázemi (CFM), čtyřvlnové míchání (FWM), nelineární rozptyl, stimulovaný Brillouinův rozptyl (SBS), Stimulovaný Ramanův rozptyl (SRS), kvantová distribuce klíčů (QKD).

LUBAJO, Lubajo Moses Wolyan. *Nové trendy v optických vláknových komunikacích*. Brno, 2018/19, 98 p. Bachelor's Thesis. Brno University of Technology, Fakulta elektrotechniky a komunikačních technologií, Ústav telekomunikací. Advised by Ing. Petr Münster, Ph.D.

Vysázeno pomocí balíčku `thesis` verze 3.03; `http://latex.feec.vutbr.cz`

ROZŠÍŘENÝ ABSTRAKT

ÚVOD

Tato bakalářská práce začíná úvodem do problematiky světla a jeho vlastností. Nejprve, základní principy světla jsou diskutovány pomocí modelů. Vlnový model má vysvětlit různá chování světla, která by jinak nemohla být vysvětlena pomocí modelu paprsku. Různé zdroje světla jsou stručně popsány s jejich příslušnými vlastnostmi. Takovými zdroji jsou diody a lasery. Zavádí se také polarizace světla. Dále je provedeno stručné srovnání optického přenosu a měděného kabelu.

V následujících kapitolách je proveden hlubší pohled na optické vlákno. Jsou popsány různé typy vláken. Jsou popsána taková vlákna jako single mode fiber (SMF), multimode fiber (MMF) a fewmode fiber (FMF). Jsou také stanovena doporučení ITU. Je popsána způsob spouštění signálu do optického vlákna. Je ukázáno, že je obtížné efektivně spouštět světlo do jednovidového vlákna s použitím svazku s nízkou prostorovou koherencí a nízkým jasem.

Později se diskutuje o ztrátě signálu v optickém vlákně. Jsou popsány útlum, ztráty rozptylu, ztráty v ohybu, absorpce a podobně. Dále se podrobněji diskutuje o přeslechu ve vláknech a mechanismu přeslechů. Je popsán model pro obnovení otevření oka včetně metod eliminace přeslechů.

Nelineární efekty v optickém vlákně. Kerrův efekt, samofázová modulace (SPM), modulace mezi fázemi (CPM) a čtyřvlnové míchání (FWM), jsou diskutovány do více podrobností, včetně jejich mechanismu a aplikací. Diskutovány jsou také nelineární efekty rozptylu. Tyto účinky jsou stimulovaný Brillouinův rozptyl (SBS) a stimulovaný Ramanův rozptyl (SRS). Jejich aplikace jsou také popsány a stručně popsány.

V další kapitole jsou diskutovány nové technologie v optických vláknech. Jsou popsány modulační formáty, jako je klíčování fázového posunu (PSK), klíčování binárního fázového posunu (BPSK), klíčování s kvadraturním fázovým posunem, klíčování s dvojitou polarizací kvadraturního fázového posunu (DP QPSK), klíčování s frekvenčním posunem (FSK) a klíčování amplitudového posunu (ASK). a popsány. DP QPSK je dále podrobněji diskutována, protože následující kapitola vyžaduje lepší pochopení základních pojmů této modulace. Popis zahrnuje princip činnosti modulátoru a demodulátoru. Blokové diagramy se také používají k vyvedení konceptů.

Praktická část se skládá ze simulace přenosu 100 Gbps pomocí DP QPSK v simulátoru PHOTOSS. Výsledky jsou diskutovány a porovnány se současným stavem a implementací v reálném světě. Rovněž je třeba zdůraznit, že v simulačním projektu je možné provést optimalizace, aby se dosáhlo větší vzdálenosti účinného přenosu, což je nutné pro mezikontinentální podmořská optická vlákna.

SHRNUTÍ A ZHODNOCENÍ VÝSLEDKŮ

Simulace byla provedena pomocí simulačního softwaru PHOTOS. Výsledky jsou diskutovány v posledních kapitolách práce. Jak již bylo uvedeno výše, stále existuje prostor pro zlepšení a optimalizaci, jinak může být simulace považována za úspěšnou.

DECLARATION

I declare that I have written the Bachelor's Thesis titled "Nové trendy v optických vláknových komunikacích" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

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ACKNOWLEDGEMENT

First of all am grateful to God for the wellbeing and good health necessary to complete this book.

I wish to express my sincere thanks to the supervisor of this bachelors thesis, Ing. Petr Münster Ph.D. I am extremly thankful and indebted to him for sharing expertise, resources,sincere and valuable guidance and encouragement extended to me. He has always beenby my side throughout the entire work.

I am also grateful to doc. Ing. Petr Číka Ph.D., Faculty Secretary, for keeping me upto date with information.

I would also like take this opportunity to express gratitude to prof. Ing. Jiří Mišurec,CSc., the Board Chairperson for the assistance, both direct and indirect.

And finally, I'd like to thank everyone who contributed to the success of this Bachelor thesis and supported me through advice and encouragements. I will always be indebted to you all.

Brno ....

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INTRODUCTION

This Bachelor's thesis begins with an introduction to light and its properties. The basic principles of light are first discussed using models. The wave model is used to explain different behaviors of light that could otherwise not be explained using the ray model. The photon model is also mentioned. Different sources of lights are briefly described with their respective properties. Such sources are light emitting diodes and lasers. Polarization of light is also introduced. A brief comparison of optical fiber transmission and copper cable is also made.

In the subsequent chapters, a deeper look at the optical fiber is taken. Different types of fiber are described. Such fibers as single mode (SMF), multimode (MMF), fewmode (FMF) are described. ITU recommendations are also laid out. Method of launching signal into an optical fiber is shown. The difficulty to efficiently launch light into a single-mode fiber using a beam of poor spatial coherence and low brightness is pointed out.

Later, signal loss in optical fiber is discussed. Attenuation, dispersion losses, bending losses, absorption among others are described. Further, a more detailed discussion is done on crosstalk in fibers and the mechanism of crosstalk. Model for restoring eye opening is described including methods of crosstalk elimination.

Nonlinear effects in optical fiber. The Kerr-effect, nonlinearites such as self-phase modulation (SPM), cross-phase modulation (CPM) and four-wave mixing (FWM) are each discussed into more details including their mechanism and applications. Nonlinear scattering effects are also discussed. These effects are the stimulated Brillouin scattering (SBS) and the stimulated Raman scattering (SRS). Their applications are also outlined and briefly described.

In the later chapter, emerging technologies in optical fibers are discussed. Modulation formats such as phase shift keying (PSK), binary phase shift keying (BPSK), quadrature phase shift keying, dual polarization quadrature phase shift keying (DP QPSK), frequency shift keying (FSK) and amplitude shift keying (ASK) are discussed and described. DP QPSK is futher discussed into more details as the following chapter requires a better understanding of the underlying concepts of this modulation. The description includes the principle of operation of the modulator and the demodulator. Block diagrams are also used to bring out the concepts.

The practical part consists of a simulation of a 100 Gbps transmission using DP QPSK in PHOTOSS simulator. The results are discussed and comparisons are made to the current status and implementation in the real world. It is also pointed out that optimizations can be made to the simulation project to achieve longer distance of effective transmission as is necessary to achieve for intercontinental undersea optical fibers.

1 LIGHT AND ITS PROPERTIES

Light is an electromagnetic radiation that can be modeled in three different models. First is the ray model. Second is the wave model and third is the photon model. Each of these models give a deeper insight of light than the one it precedes. Characteristics of light from the communication point of view.

- **Intensity:** Intensity is the measure of the rate at which light energy is delivered to a unit of surface, or energy per unit time per unit area. For instance, the intensity of the sunlight on a solar panel, multiplied by the panel's area, would tell how much power (energy per unit time) is available to run a solar water heater. So for a given power, when the light is confined to a small beam (i.e. reduce the area), the light appears brighter or high intensity. A laser appears brighter than a florescent tube even if its power is smaller because the light from a laser is focused to a very small cross sectional area.
- **Wavelength (color):** Even if the optical wave that is used in optical communication fibers does not lie in the visible part of the spectrum, the notion of color is used to characterize wavelength, lamda (λ). Depending on the loss performance, λ can be chosen in either 1300 nm or 1500 nm region. The choice of λ has a direct effect on the loss performance of an optical fiber as will be shown in the subsequent sections. This is the signal to noise ratio (SNR) of the optical system.
- **Spectral width (purity of color):** this is the wavelength range at which the emission takes place. It is denoted by $\delta\lambda$. The spectral width is directly related to the data rate. The smaller the spectral width, the higher the bandwidth or the data rate of an optical system.
- **Polarization:** as already mentioned, light can also be viewed as a transverse electromagnetic wave. That means, the underlying oscillation (the oscillating electric and magnetic fields) is along directions perpendicular to the direction of propagation. Light is said to be linearly polarized if its oscillation is confined to one direction, i.e., the direction of the oscillation of the electric field is defined as the direction of polarization. Lights from natural sources emit unpolarized lights. This type of polarization is when light consists of many wave trans whose directions of oscillation are completely random. It is called incoherent light. Light can also have an elliptical or circular polarization. In general, the elliptical polarization can degenerate into a linear or a circular polarization. This parameter is important because it describes the wave nature of light.

1.1 Optical Receivers

The detection of light is based on the excitation of electrons by photons in photosensitive materials. This process generates an electric current whose average is proportional to the power of the incident light. The fluctuation around this average are caused by shot noise and are negligible in amplified systems where the dominant noise contribution comes from spontaneous emission[18].

The great majority of optical receivers used in optical communication are based on direct detection of light and are therefore sensitive only to the incident optical power. Receivers that are also capable of detecting the optical phase are called *coherent receivers*, and their principle of operation relies on the coupling of the incoming optical fields with a strong local oscillator prior to photodetection [19]

1.2 Light propagation in optical fiber

In this section, transmission parameters associated with Optical Communication and various properties of light are discussed.

1.2.1 Wavelengths, Frequencies, and Channel Spacing

Frequency f, wavelength λ and velocity (speed of light c) are interrelated as shown in equation 1.1.

Wavelength Division Multiplexing

$$c = f \times \lambda \tag{1.1}$$

Where:
c = speed of light in free space ($3 \times 10^8 \, ms^{-1}$),
f = frequency, and
λ = wavelength.

The speed of light in fiber is less than c, around $2 \times 10^8 \, ms^{-1}$ and the wavelengths are correspondingly different [1]. Wavelength is measured in units of manometers (nm) or micrometers (μm or microns).

In optical fiber communication, the wavelengths of interest are centered around 0.8, 1.3, and 1.55 μm. These wavelengths are not visible to the human eye because they lie in the infrared region of the spectrum, lower than the visible light. Using $c = 3 \times 10^8 \, ms^{-1}$, a 1.55$\mu$m wavelength corresponds to a frequency of 193 THz ($193 \times 10^{12} \, Hz$).

Channel spacing is another important parameter of interest. This is the spacing between two wavelength frequencies in a Wavelength Division Multiplexing (WDM).

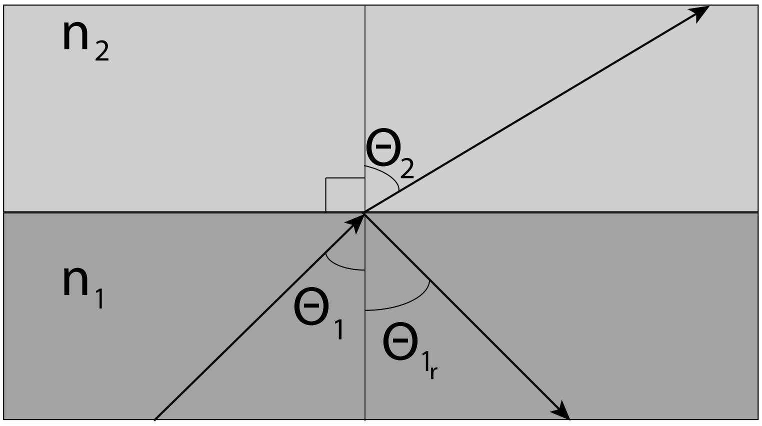

Fig. 1.1: Reflection and refraction of light rays at the interface between two media [1].

Channel Spacing can be measured in either wavelengths or frequencies. Making f the subject of equation 1.1 and differentiating around a center wavelength λ_0, the relationship between frequency spacing Δf and the wavelength spacing $\Delta\lambda$, equation 1.2.

$$\Delta f = \frac{c}{\lambda_0^2}\Delta\lambda \tag{1.2}$$

This relationship is accurate only for wavelength (or frequency) spacing smaller than the actual channel wavelength (or frequency). This is usually the case in optical communication systems [1].

1.3 Geometric optics

Using the so called *ray theory* or *geometric optics*, a simplified understanding of light propagation can be obtained. This approach has a limitation in that, the radius a of the core of the optical fiber has to be much larger than the operating wavelength λ.

In the geometric optic model of light, light is considered as consisting of "rays" that propagate in straight lines within a medium (or material). It gets reflected and/or refracted at the interfaces between two materials (which have different refractive indices n_1 and n_2).

When a light ray from medium 1 is incident on the interface between medium 1 and medium 2 with an *angle of incidence* θ_1 (angle between the *incident ray* and the

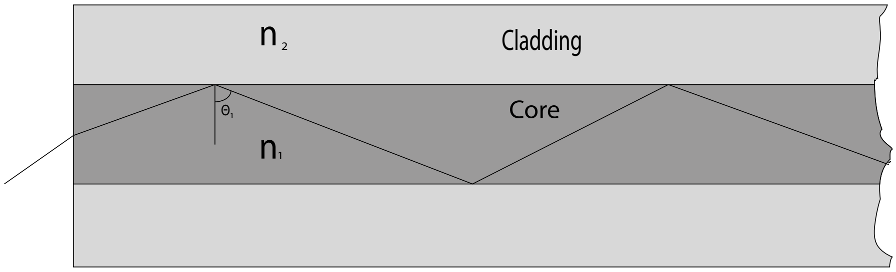

Fig. 1.2: Propagation of light rays in optical fiber by total internal reflection [1].

normal to the interface between the two media), part of the energy is reflected into medium 1 as teh *reflected ray* with an angle of reflection θ_{1_r} This angle, is equal to the angle of incidence, θ_1 according to the laws of reflection. Part of the energy of the incident ray is refracted into medium 2 with an *angle of refraction* θ_2. Similarly, the angle of refraction is the angle between the normal and the refracted ray [1]. Fig. 1.1.

The laws of geometric optics state that

$$\theta_1 = \theta_{1_r} \tag{1.3}$$

And

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.4}$$

Equation 1.4 is known as *Snell's law.*

When the angle of incidence, θ_1 is increased, the angle of refraction θ_2 also increases. There comes a point when $\theta_2 = 90°$ or $\pi/2$ radians. The value of θ_1 when θ_2 is $\pi/2$ radians is the *critical angle.* The critical angle is the smallest angle of incidence for which there is no refracted ray and it is equal to $\sin^{-1} n_2/n_1$. For larger values of θ_1, all the incident light rays become totally reflected and there is no refracted ray. This phenomenon is called *total internal reflection.*

From geometric optic point of view, light propagates through an optical fiber by means of series of total internal reflections that occur at the core-cladding interface, Fig 1.2. In this figure, light travels through air into the core. The refractive index of air is n_0.

Using Snell's law, it can be shown that, only the rays that satisfy the inequality equation 1.5 at the air-core interface will undergo total internal reflection. The rays that satisfy the equation and thus propagate through the fiber are called *guided rays* and the angle θ_0^{max} is called the *acceptance angle* and it is $\approx 12°$ [1].

$$\theta_0 < \theta_0^{max} = \sin^{-1} \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \tag{1.5}$$

1.3.1 Optical devices

Developments in the field of optical communication devices are in the direction of integrated optics known as Planar Lightwave Circuits (PLCs) or Photonic Integrated Circuits (PICs) [20]. In an effort to reduce the cost of production of optical devices, increase the functionality of telecommunication networks and to limit the impact on the environment in relation to the amount of carbon-footprint emission resulting from the use of electricity, integration has become an important tool. The development of optical circuits suggests that cheaper monolithic solutions will replace the current hybrid solutions [20].

1.3.2 Light sources

The principal light sources used for optical fiber communication applications are heterojunction-structured semiconductor laser diodes (ILDs) and Light Emitting Diodes (LEDs). A heterojunction consists of two adjoining semiconductor materials with different band-gap energies [15], [21].

These devices are preferred for fiber optic communication because:

- they have adequate output power suitable for a wide range of applications,
- their output power can be directly modulated by varying the input current to the device,
- they have high efficiency,
- their dimensional characteristics are compatible with those of optical fibers.

The major difference between laser diodes and LEDs is that, the optical output from a laser is coherent whereas that from a LED is incoherent. A coherent source produces optical energy in an optical resonant cavity. The optical energy released from this cavity is highly monochromatic and the output beam is very directional.

An incoherent source has no optical cavity for wavelength selection. Since the emitted photon energies range over the energy distribution of the recombination electrons and holes, the output radiation has a broad spectral width [15]. This usually lies between 1 and $2k_BT$ where k_B is Boltzmann's constant and T is the temperature at the pn junction.

Semiconductor LEDs are usually the best light source for optical systems requiring bitrate less than approximately 100 to 200 Mbps together with multi-mode fiber-coupled optical power of tens of microwatts. Since no thermal or optical stabilization circuits are needed, LEDs require less complex drive circuitry and they can be fabricated less expensively with higher yields [15].

1.4 Linear Polarization

The electric or magnetic fields oa a train of *plane linearly polarized waves* traveling in direction $\mathbf{k}$ cab be represented by the general form

$$\mathbf{A}(x,t) = \mathbf{e_i}\mathbf{A_0}j(wt - \mathbf{k}.\mathbf{x}) \tag{1.6}$$

With $\mathbf{x} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z$ representing position vector and $\mathbf{k} = k_x\mathbf{e}_x + k_y\mathbf{e}_y + k_z\mathbf{e}_z$ representing the wave propagation vector [15]. In 1.6, A_0 is the maximum amplitude of the wave, $\omega = 2\pi v$, where v is the frequency of the light and the magnitude of the wave vector $\mathbf{k}$, $k = 2\pi/\lambda$ is known as the *wave propagation constant*

Polarization (also polarisation) is a property applying to transverse waves that specifies the geometrical orientation of the oscillations. In later sections, this property of light is used to double the information that is transmitted through a fiber by a modulation format known as Dual Polarization Quadrature Phase Shift Keying (DP QPSK).

2 OPTICAL COMMUNICATION

The beginning of the New Millennium shows dramatic changes in the telecommunication industry that have far-reaching implications for our daily lifestyle. First, there is a continuing, relentless need for more capacity in the network. This is due to various factors. The greatest factor is the tremendous growth of the Internet and the World Wide Web, both in terms of the number of users and the amount of time spent by users on-line. This generates increasingly large traffic that reflects into need for more bandwidth.

Businesses today rely on high-speed networks to conduct their businesses. Large business enterprises have locations all around the world. The network is used to interconnect these locations as well as between companies for business-to-business transactions.

Optical network provides much higher bandwidth compared to copper wires/cables and is more immune to various types of electromagnetic interference. In addition to providing enormous capacities in the network, an optical network provides a single infrastructure over which a variety of services can be offered.

For any data over a few tens of megabits per second and a distance from over a kilometer upwards, optical fiber is the preferred means of transmission of data over the network [1].

2.1 Advantages over copper wires

Systems operating on metallic conductors will gradually be replaced by telecommunication systems transmitting information over optical fiber. Metallic conductors in their current form have come to the limits of their functional potential [17]. The following are advantages of fiber optics over copper wires:

- **Electrical isolation:** Fiber optics allow transmission between two points without regards to the electrical potential between them.
- **Grounding:** since fiber optic cables do not have any metal conductors, they do not pose the shock hazards inherent in copper wires.
- **Lower loss:** Optical fibers have lower attenuation than copper conductors. This allows longer cable runs with fewer repeaters.
- **Decreased size, weight and cost:** Compared to the copper counterparts of equivalent signal carrying capacity, fiber optic cables are easier to install, weigh 10 to 15 times less, require less duct space and costs less than copper.
- **Increased bandwidth:** A significantly higher information carrying capacity is provided by the high signal bandwidth of optical fibers. Typical bandwidths for multi mode(MM) fibers are between 200 and 600 MHz-km and greater

than 10 GHz-km for single mode (SM) optical fibers. Meanwhile the typical bandwidth values for electric conductors are 10 to 25 MHz-km.

- **Electromagnetic Immunity:** There is a very low EMI when signal is transferred in optical form. Even if light is an electromagnetic wave, electromagnetic interference is strong when the distances are comparable to the wavelength. When communication operates at microwave frequencies, the wavelengths are about the orders of a few tens of centimeters. So in a typical electronic circuit, there is a coupling between different components since their separation is comparable to the wavelength. On the other hand, optical wavelengths are in orders of microns. So electromagnetic interference would occur only if the the distance between these devices are in microns. This gives optical communication a better EMI performance.
- **Security of transmission:** When signal is put in a medium such as an optical fiber, the signal is difficult to tap without being detected. This is not true with twisted pairs since there is an electromagnetic . A coupling device can couple the fields since no light leaks Since no radio frequency signals (RF signals) are emitted by optical fibers, they are difficult to tap into without being detected.
- **No sparks or shorts:** Fiber optics do not emit sparks or cause short circuits, which is important in explosive gas or flammable environments.

2.2 Challenges in optical communications

The capacity of the optical communication link is subject to the equipment available and its electronic, the type of transmission signal and the communication channel. Figure 2.1 shows all three elements which are equally important for correct and immediate delivery of telecommunication data, i.e., new optical devices, improved communication techniques and new architecture for optical networks [20].

There are many studies based on new modulation methods and new models for data transmission, which can also handle non-linear and randomly changing optical communication channels, whereby the objective is to provide higher bit rates and better signal or service quality [20].

As shown in Figure 2.2, the transfer of the optical fiber, on the one hand limits the low signal-to-noise ratio, and on the other, a too high nonlinearity is becoming noticeable at large distances and high optical powers. The transfer can be improved by reducing the attenuation and non-linearity in an optical fiber, wherein Large-Aeff Pure-Silica Core Fiber (LA-PSCF) optical fibers are essential as they introduce the lowest attenuation (up to 0.161 dB/km) and two times smaller nonlinearities known in a standard single-mode fiber [20].

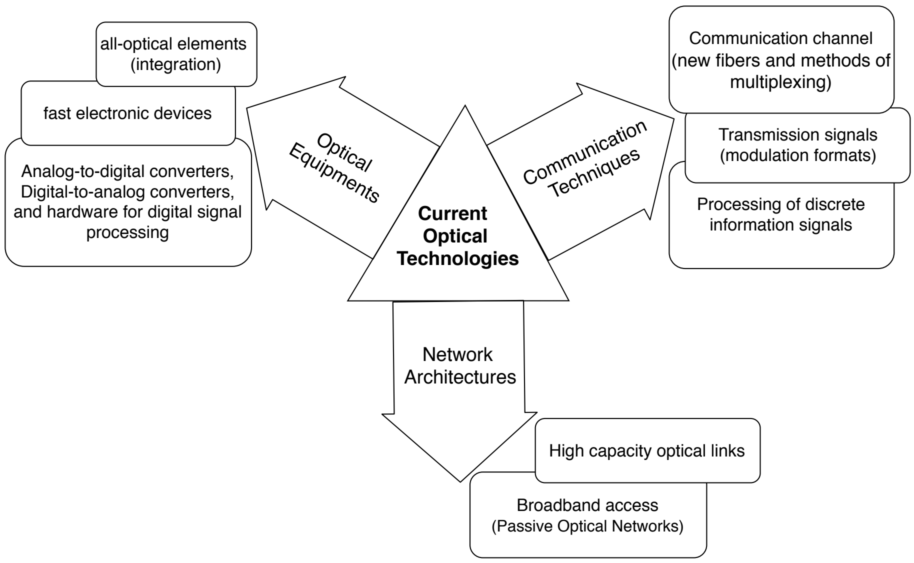

Fig. 2.1: Three directions of development in optical communications.

[20].

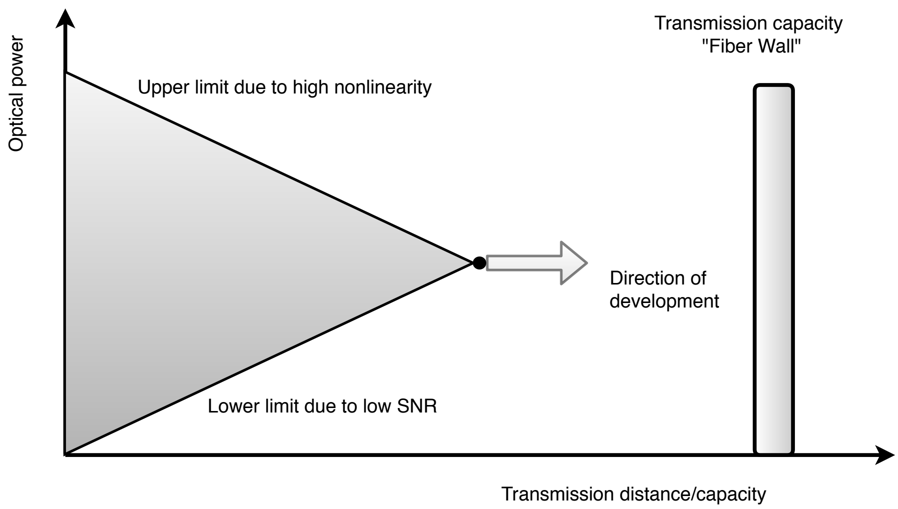

Fig. 2.2: Transmission limits for optical fiber communications

[20].

3 OPTICAL FIBER

In this chapter, different standards of optical fibers used in optical fiber communication are introduced. They are then described into details including their manufacture and the characteristics. Recommendations are given for the types of fiber used in different types of connection such as which optical cables are preferred or used in transcontinental undersea cables and last mile cables. The manufacture of optical cables is also briefly described. Furthermore, the types of optical cables are described such as the singlemode (SM), multimode (MM), fewmodes (FM) etc. Lastly, a table of comparison is laid out to summarize the different parameters of the types of optical fibers.

3.1 The optical fiber

An **optical fiber** is a dielectric wave-guide that operates at optical frequencies. It consists of a cylindrical *core* surrounded by *cladding.* Fig. 3.1 shows a cross-section of an optical fiber. Silica (SiO_2) is the primary element used in the construction of both the core and the cladding. SiO_2 has a refractive index n of about 1.45. A fiber confines electromagnetic energy in form of light to within its surfaces and guides it in a direction parallel to its axis [15].

The ratio of the speed of light in vacuum to the speed of light in a given material is the refractive index of that material. To increase the refractive index in the core and/or the cladding, several impurities (dopants) are introduced. This is done so that the refractive index of the core is higher than that of the cladding. As will later be discussed, the higher refractive index of the core enables light to be guided by the core propagating it through the fiber. The refractive index of silica can be increased by using materials such as germanium and phosphorus. These dopants are used for the core since they increase the refractive index. To reduce the refractive index of the cladding (relative to the core), dopants such as boron and fluorine are used.

There are basically three parameters that are responsible for the actual properties of optical fibers[2];

- The material used in the core and in the cladding which determines the attenuation and the chromatic dispersion,
- The core diameter is responsible for the number of modes that can pass the fiber,
- The refractive index profiles determine the mode dispersion.

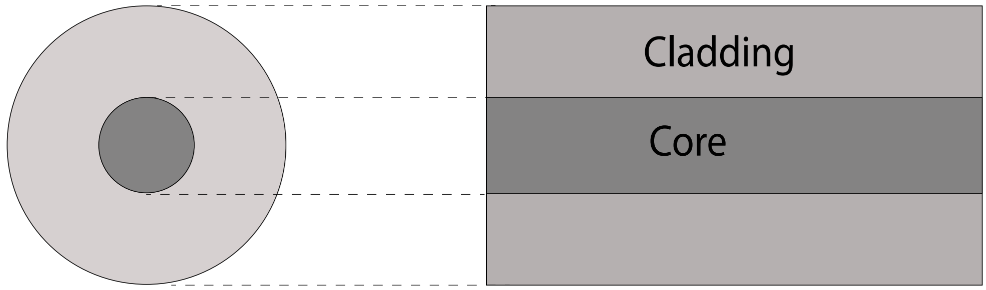

Fig. 3.1: Cross section and longitudinal section of an optical fiber showing the core and the cladding region [1].

Step Index Profile Fibers

In this type of indexing, a simple optical cladding surrounds a homogeneous core. A protective material is always included in the cable. In practical step-index fibers the core of radius a has a refractive index n_1. This is surrounded by a cladding of lower refractive index n_2, where;

$$n_2 = n_1(1 - \Delta)[15] \tag{3.1}$$

The parameter Δ is the *core-cladding index difference*.

The refractive index of the core is usually taken as 1.48 whereas that of the cladding is correspondingly smaller and that of air is often taken as 1 (the refractive index of vacuum). Δ is nominally 0.01. Typical values range from 1 to 3 percent for multimode fibers and 0.2 ro 1.0 percent for single-mode fibers [15]. The refractive index step determines the numerical aperture (NA) and thus the acceptance angle. Since the NA exceeds the value of 1, an acceptable angle of 90 is valid [2].

Graded Index Profile Fibers

In this type of optical fiber design, the core refractive index decreases continuously with increasing radial distance from the center of the fiber. The refractive index is generally constant at the cladding.

The refractive index difference Δ for a graded-index fiber is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \tag{3.2}$$

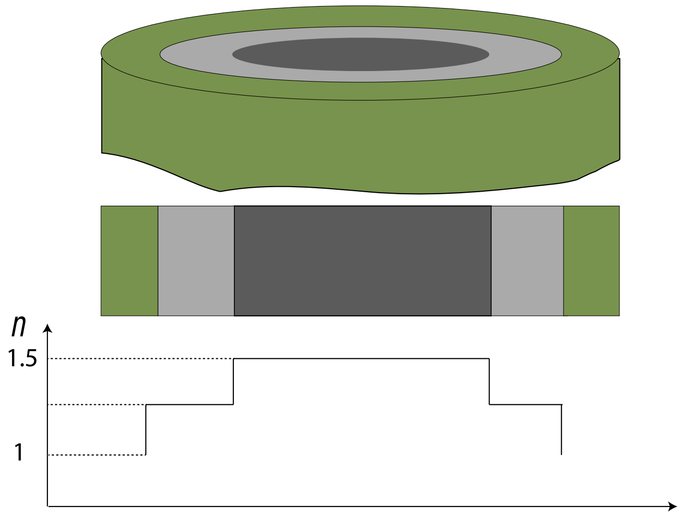

Fig. 3.2: Structure of a step index profile fiber[2].

3.2 Types of optical fibers

In optical fiber communication, there are different grades of fibers just as there are also different grades of copper cables. Even though in the later sections, the newer trends will be discussed, the fundamental divide of optical fibers is between *single-mode* and *multi-mode* fiber.

A ***mode*** can mean many different things depending on the context it is being used; different discrete eigen-modes in a waveguide, different directions, different polarization, etc. A generalized definition is: "An electromagnetic mode is electromagnetic power that exists independent and different from other electromagnetic power" [3]. Figure 3.3 shows different modes used in waveguides.

There are essentially two types of fibers - singlemode fiber and multimode fiber.

Single-mode and multi-mode are very different and are used in different link types. The other grades of optical fiber are *few-mode* and *many-mode* optical fibers. The structural characteristics of an optical fiber dictates the transmission properties of an optical waveguide. It has a major effect in determining how an optical signal is affected as it propagates along the fiber.

3.2.1 Single-Mode Fiber

Single-mode fiber, Fig. 3.4. (c), is used for longest distance and highest bandwidth optical transmission because it intermodal dispersion is eliminated by the scale of

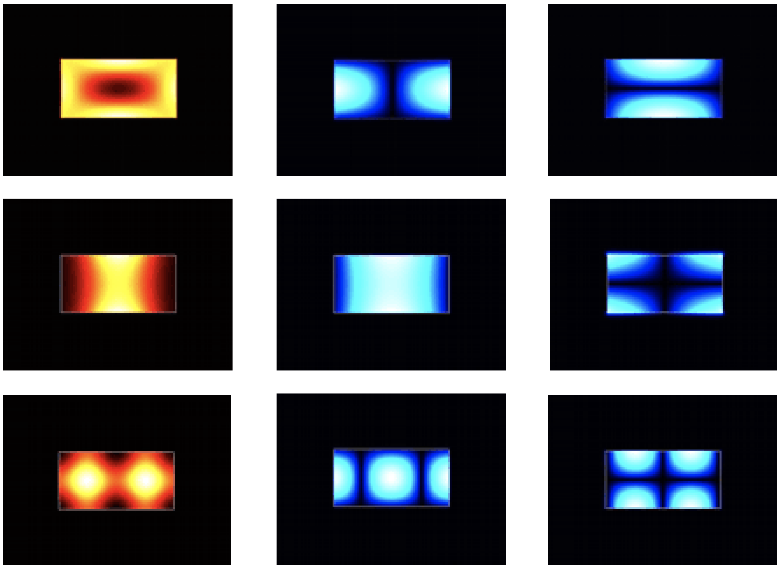

Fig. 3.3: Modes used in waveguides [3].

the core. The core of a single-mode fiber is in the same scale as a wavelength that restricts itself to the “fundamental” spatial core. They are constructed by letting the dimension of the core diameter be a few wavelengths (usually 8-12) and by having a small index differences between the core and the cladding [15]. To understand the behavior of single-mode fiber, a true electromagnetic wave treatment is necessary. This is because of the thin core of the fiber.

In any ordinary single-mode fiber, there are two independent, degenerate propagation modes which are very similar, but their polarization planes are orthogonal, which can be chosen as vertical and horizontal.

3.2.2 Multi-Mode Fiber

Typical multi-mode fibers (MMF) have cores much larger than the wavelength of light [1], and thus the overall behavior can be described by simple optical geometry. Multimode fiber has a larger core size of 50 to 62.5 microns than single mode fiber core of 9 microns, resulting in different modal distortion [4]. A large number of modes (or simply, independently propagating paths of the optical signal) are carried by MMF. They can carry hundreds of modes. Intermodal dispersion occurs since signals on different modes have different velocities. Dispersion, in most situations, result in broadening of signal pulses. Signal pulses correspond to data bits. Intermodal dispersion leads to overlap of of pulses representing adjacent bits which creates distortion to the signal. This phenomenon is called *Inter-Symbol Interference* (ISI) [1].

MMF are aimed at transmitting and receiving independent information inside each mode thus greatly increasing the capacity of a single core. It is nowadays used on very short distances of up to 600 m, this is due to the difficulty of maintaining the stability across all the modes as a result of cross-talk (Sec. 3.8) among the several modes, bending, fiber imperfections and twisting [22].

There are several challenges to be addressed, such as the need of heavy processing capabilities and miltipath propagation techniques like MIMO (Multi Input Multi Output), when using MMF in very large distances such as transoceanic. These techniques are used to enable separation of each mode when they are received [22].

Multimode fiber may be divided into step-index , Fig. 3.4 (a), and graded-index fiber, Fig. 3.4 (b).

Graded index and step index fibers

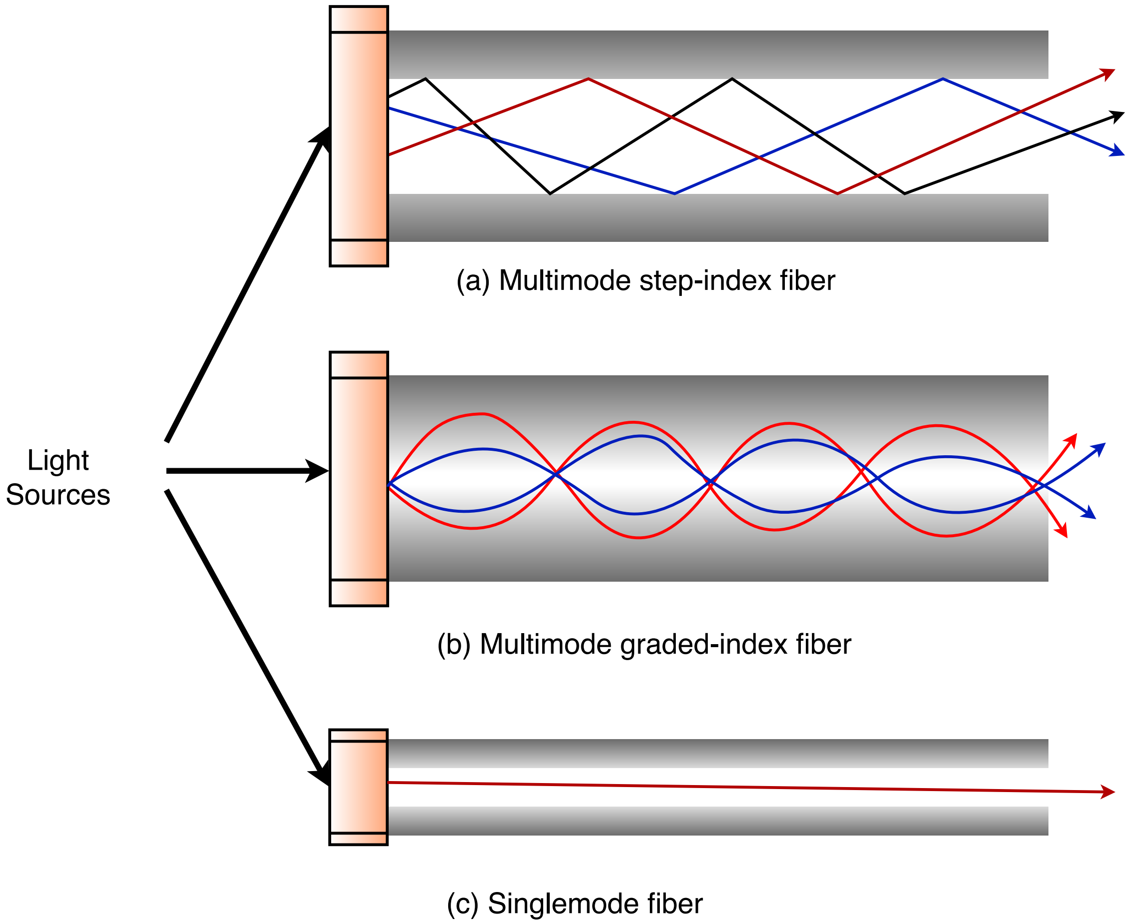

Fig. 3.4: Structure of a step index profile fiber[4].

Core diameter (μm)	**Clad diameter** (μm)	**Numerical aperture**
50	125	0.19 - 0.25
62.5	125	0.27 - 0.31
85	125	0.25 - 0.30
100	140	0.25 - 0.30

Tab. 3.1: Preferred sizes of multimode glass optical fibers and their corresponding numerical apertures [15].

Few-Modes Fiber

Few-Mode Fibers (FMF) is a simpler case of MMF

Fiber capacity can be increased by [23]:

- reducing fiber loss,
- increasing the Optical Signal to Noise Ratio, OSNR,
- reducing the channel spacing,
- increasing the low loss window to fit more WDM channels ,
- making better us of already existing windows by employing higher order modulation formats.

3.2.3 Multi-Core Fiber

A multi-core fiber includes an even number of six or more of cores and a clad that surrounds the outer circumferential surfaces of the cores. The cores are formed of two types of cores and in which an effective refractive index difference in a fundamental mode is 0.002 or less in a predetermined range or more that the effective refractive index difference in the fundamental mode is varied according to a core pitch. Two types of the cores are alternately and annularly disposed at regular spacing. A difference in the mode field diameter of light propagating through the cores is 1 µm or less.

3.3 Construction and different standards

Optical fibers links have become so popular and are very widely used for different types of connection. For this reason, standards had to be laid out to assist suppliers and their customers to meet specific telecom applications. According to the ITU-T recommendations, there are the following single-mode fibers (group G):

	Type	Core/Clad (um)	FE (100Mb)	Gigabit GbE	10GbE	40GbE	100GbE	40G SWDM4	100G SWDM4
Multimode	OM1	62.5/125	2 km	275 m	33 m	-	-	-	-
	OM2	50/125	2 km	550 m	82 m	-	-	-	-
	OM3	50/125	2 km	800 m	300 m	100 m	100 m	240 m	75 m
	OM4	50/125	2 km	1100 m	400 m	150 m	150 m	350 m	100 m
	OM5	50/125	2 km	1100 m	400 m	150 m	150 m	440 m	150 m
Singlemode	OS1/OS2	9/125	40 km	100 km	40 km	40 km	40 km	-	-

Tab. 3.2: Speeds of fibers[16].

3.3.1 ITU recommendations

ITU G.651.1

Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network.
The main focus of this standard is a specific *segment* (a network in a multi-tenant building). This fiber is 50/125 µm graded index multi-mode optical fiber. They are suitable for use in the 850 nm or 1300 nm region. Alternatively, they may be used in both wavelength regions simultaneously [5]. It is extensively used for datacom system in enterprise buildings with system bit rates ranging from 10 Mbits/s up to 10 Gbits/s.

ITU G.652

Characteristics of a single-mode optical fiber and cable.

Type G.652 This is the original standard optical single-mode fiber sometimes designated by the abbreviation USF (Unshifted Fiber) according to the Corning Company specification. It has a Mode Fiber Diameter (MFD) in the range 8.6 ~9.5 µm. It has a maximum cable cutoff wavelength of 1260 nm and Zero Dispersion Window (ZDW) in the range 1300~1324 nm [5]. It is sometimes designated by the abbreviation USF (Unshifted Fiber). In view of the typical change in the refractive index at the interface between the core and the cladding, these fibers are referred to as Matching Cladding [17].

Type G.652.C Unlike the ordinary fiber G.652, this currently available new type of fiber can be used over the whole wavelength range. This enables the utilization of all the available transmission bands, including band E (1360-1460 nm).

It was formally impossible to use this band due to increased insertion attenuation of conventional optical fibers in this region caused by resonance on absorbed water ions OH^-. These ions permeated the fiber during manufacture [17].

Type G.652.D This fiber is an all-wave fiber and it is compatible with all the G.652 optical fibers. It is the most modern in the several categories of the G.652 characterized by low attenuation in cable (maximum of 0.3 dB at 1550 nm), good Polarization Mode Dispersion (PMD) performance (better than $0.2\,\mathrm{ps/km^{\frac{1}{2}}}$) link design value, and low water peak (LWP) attenuation at 1330 nm. Because the E-band is available on account of the LWP loss, the G.652D fiber is optimized for full spectrum use at data rates up to 10 Gbps (STM-64) [5].

ITU G.653

Characteristics of a dispersion-shifted, single-mode optical fiber and cable
They are referred to as Dispersion Shifted fibers (DSF) and the standard has been developed with the aim of suppressing chromatic dispersion for the wavelength 1550 nm. With a single wavelength in operation, they are used for long distance transmission with high speed. There was a side effect when multiplexing using DWDM with several wavelengths. There is overlapping of individual wavelength and crosstalk and appearance of parasitic neighboring channels [17]. The embedded base of DSF in some countries has been upgraded by moving to L-band systems for DWDM [5].

ITU G.654

Characteristics of a cut-off shifted single-mode optical fibre and cable
These were developed as a special variant of the G.652 fibers[17]. They were standardized to provide lower loss and allow higher Mode Field Diameter (MFD). low attenuation limits of 0.22 dB/km at 1550 nm with as high cutoff wavelength as 1530 nm and a high PMD specification (as low as $0.2\,\mathrm{ps/km^{\frac{1}{2}}}$) [5]. Because they are expensive, their usage is limited mostly to extremely long-haul submarine transmissions cables without repeaters and amplifiers.

ITU G.655

Characteristics of a non-zero dispersion-shifted single-mode optical fiber and cable
There were a series of obstacles for high bit-rate transmission systems that were designed using wideband EDFAs and the low fiber loss in the C-band. The high chromatic dispersion of G.652 fiber at 1550 nm limits capacity due to dispersion related signal impairment. The zero dispersion of DSF near 1550 nm results in signal

impairment related to nonlinear propagation effects. The solution to this problem was shifting the ZDW away from the C-band. The type 6.55 fibers with shifted non-zero dispersion (NZ-DSF, Non-Zero Dispersion Shifted Fiber) are optimized for transmission in the 1550 nm band. Unlike the G.653, these fibers do not have zero dispersion for the 1550 nm wavelength and these fibers (G.655) are mainly used in wide-range optical network.Too much non-linear effects would show in the 1550 nm wavelength which necessitates low non-zero dispersion. This fiber is designed for high transmission speeds and for the operation of DWDM technology [17][5]. The key feature is low (but nonzero) chromatic dispersion in the C-band and low PMD ($<0.2\,\mathrm{ps/km}\frac{1}{2}$). These fibers support 40 Gpps (STM-256) rates of transmission over long distances [5].

ITU G.656

Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport
These fibers are optimized for transmission region in the 1460-1625 nm band [17] to decrease ISI(Inter-Symbol Interference) that limits uncompensated CWDM transmission [5]. These are fibers with shifted non-zero dispersion. Like the ITU G655, they are also NZ-DSF.It is CWDM/DWDM optimized. The fibers according to ITU G.656 allow highest performance with optical channels spaced over a wide band at 40 Gbps and over long distance. The maximum chromatic dispersion is set to be between 2 to $14\,\mathrm{ps{\cdot}nm/km^{-1}}$, and the maximum polarization dispersion is $.02\,\mathrm{ps}/\sqrt{km}$ [17].

ITU G.657

Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network The ITU G.657 has been adapted for the huge experience with the installation and operation of single-mode fiber and cable based network. This standardization is to support optimization for resistance in bending in comparison to the G.652 single-mode fiber cables. This is done by means of two categories od single mode fibers:

Category A Can be deployed throughout access network (internal/external cabling) and is fully compliant to ITU G.652 single-mode fibers.

Category B Is capable of low values of microbending losses at very low bending radii and not necessarily compliant with ITUT-T G652. It is intended for use inside buildings or near buildings [5].

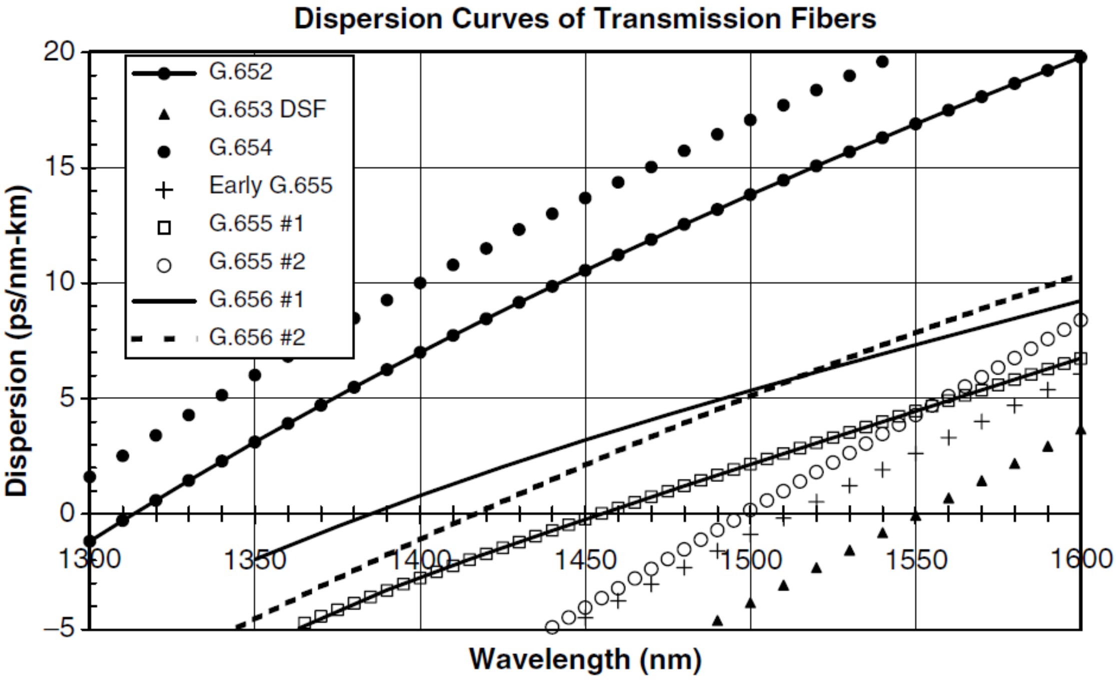

Fig. 3.5: Dispersion curve for transmission fibers [5].

Category C Is a new type of fiber that is resistant to microbending up to a radius of 5 mm [17].

Fig. 3.5 shows the dispersion curves of transmission of different fibers.

3.4 Launching light into an optical fiber

It is hard to efficiently launch light into a single-mode fiber using a beam of poor spatial coherence and accordingly low brightness. Taking example of a light bulb launch, assuming ideal absorbance of the filament and disregarding a few percent of losses e.g. from reflections at the bulb's glass, the lens and the fiber end, ideally a launch can be made into the fiber the power corresponding to two radiation modes (considering two polarization directions):

$$P = s\frac{hv}{e^{\frac{hv}{k_bT}} - 1}\Delta v[24] \tag{3.3}$$

where v is the optical frequency, T is the filament's temperature, and Δv is the optical bandwidth. This is part of Planks formula for black body radiation (missing the part with mode density considering two polarization directions).

The brightness can be increased by many orders of magnitude by using a superluminescent source, e.g. in the form of a superluminescent diode. This allows one to launch tens of milliwatts of power, if not more [24]. Typically, a single-mode silica

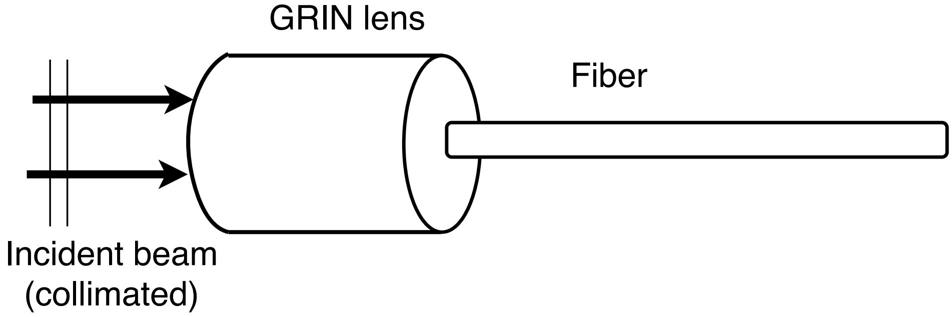

Fig. 3.6: Dispersion curve for transmission fibers [6].

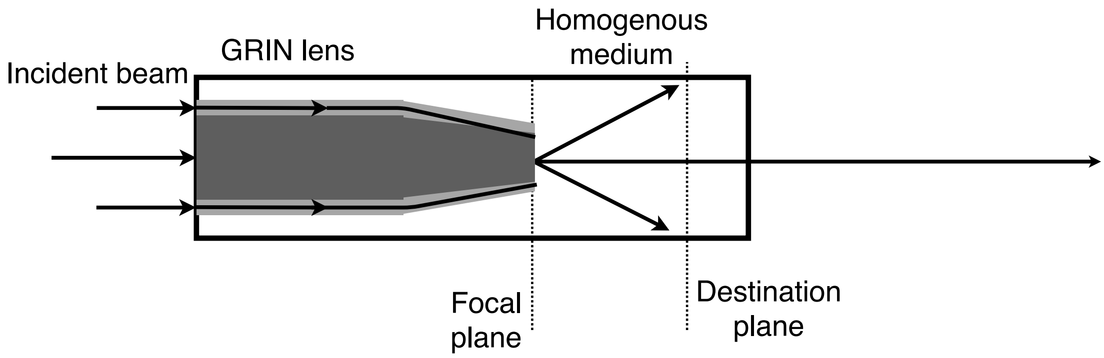

Fig. 3.7: Method of computing the light-amplitude-distribution at the focal plane of the GRIN lens [6].

glass fiber has a mode profile that is well approximated by a Gaussian beam. At λ = 1.55 μm, the Gaussian mode has diameter of ~10 μm [6].

Light can be launched into a fiber by placing the polished end of the fiber in contact or close proximity to the polished end of another fiber with matching mode profile (the wire that carries signal). It can also be launched by a coherent beam of light focused directly onto the polished end of the fiber [6]. If the fiber's core and the focus spot are well aligned, and has the same amplitude and phase distributions (as the fiber's mode profile), then the entire incident optical power is carried by the launched mode into the fiber [6]. However, in general, this conditions are not fulfilled and therefore, only a fraction of the incident optical fiber will be launched into the fiber. The numerical value of this fraction is commonly referred to as *coupling efficiency*, η.

With reference to Fig. 3.7, ray-tracing begins at the entrance facet, and continues through the focal plane to the destination plane. The destination plane is the far end of the focused spot. The traced rays are used at the destination plane to construct the emergent wave-front which is subsequentlyl back-propagated to the focal plane

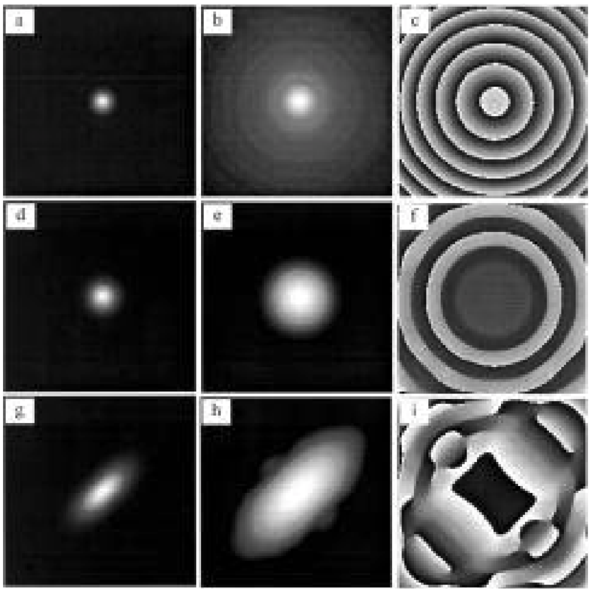

Fig. 3.8: Plots of intensities(left), log_intensity (middle) and phase (right) at the rear facet of the GRIN lens in Fig. 3.7 [6].

at the exit facet if the GRIN lens. The far-field or Fraunhofer formula of the classical diffraction theory is used to back-propagate [6].

Effect of beam size and astigmatism

Fig. 3.8 shows 8 plots of intensity (left column), log_intensity(middle column) and phase (right column) at the rear facet of the GRIN lens of Fig. 3.7 under three different conditions

3.5 Signal Loss in optical fiber

Loss is inherent nature of optical fibers. Loss is usually classified into: absorption loss, scattering loss, waveguide loss and bending loss, etc. in accordance with different generation mechanisms. There is interaction between photons and atoms when light-wave propagates in optical fiber media[25].

Scattering loss is generated by collision of photons with substrate atoms, microscopic changes in optical fiber density and uneven composition distribution during or structural defects that are generated during the manufacturing process of the optical fiber.

Attenuation is the reduction in power of the light signal as it is transmitted through a medium [26]. It is caused by passive media components, such as cables, cable splices, and connectors. Attenuation is relatively low in optical fibers than other media.

Attenuation in optical fibers is mainly due to:

- diffusion on inhomogeneities
- absorption by the media in which the radiant light is propagating
- radiation from the fiber

Dispersion losses

This is caused by to the fact that molecules randomly distributed in amorphous material actually from micro-inhomogeneities of the refractive index of the material. A dispersion losses that appear on a material is called Rayleigh's scattering losses when the minor impurities and the inhomogeneities are dimensionally small in comparison with the wavelength. The losses are inversely proportional to the fourth power of the wavelength of propagating radiation (equation 3.4) and they rapidly increase towards the UV region of the spectrum. Rayleigh's scattering is characterized by its one-directionality. The Rayleigh's mechanism arises because of fluctuations in the density of the medium(silica) at the microscopic level[1].

The loss coefficient (α_R) due to Rayleigh's scattering at a wavelength λ, is given by equation 3.4. The constant A is called the Rayleigh's coefficient.

The current best value of fiber loss is about 0.2 dB. One of the possibility to reduce losses below that is to operate at higher wavelengths so as to reduce the loss due Rayleigh's scattering. On the other hand, the material absorption of silica is quite significant at such higher wavelengths.

$$\alpha = \frac{A}{\lambda^4} \tag{3.4}$$

Bending Loss

For various reasons, optical fibers need to be bent when deployed in the field and within equipment, this causes power to "leak" out of the fiber core into the cladding resulting in loss. A characteristic of a bend is its radius of curvature - (*bend radius*). When the bend radius is smaller, the loss is larger. The bending loss at 1550 nm is higher than at 1330 nm. By ITU-T specifications, the bending loss at 1550 nm per 100 turns of fiber wound in with a radius of 37 mm, must be in the range 0.5-1 dB depending on the fiber type. Since the loss due to bending increases rapidly as the bend radius is reduced, care must be taken, especially within equipment, to avoid sharp bends.

Dispersion is the phenomenon whereby different components of a signal travel at different velocities [1]. Dispersion mostly limits the data rate of a digital signal by spreading signal pulse over time.

Absorption loss

Results from photons gradually transferring their energy into atoms. Impurities and optical matrix materials are the main factors influencing the absorption loss [25]. Absorption loss is classified based on the different absorption subjects into intrinsic absorption loss, atomic defect absorption loss and impurity absorption loss. Material absorption includes absorption by silica as well as impurities in the fiber. The material absorption of pure silica is negligible in the entire 0.8-1.6 μm band that is used in optical communication system [1]. The loss in the wavelengths of interest has now been reduced to levels that are negligible so that the loss due to Rayleigh's scattering is the dominant in the 1.3 μm and the 1.55 μm.

Loss and bandwidth windows The following equation can be used to model the loss incurred by propagating down a fiber. The output power $P_{(out)}$ at the end of a fiber of length L is related to the input power $P_{(in)}$ by

$$P_{out} = P_{in}e^{-\alpha L} \tag{3.5}$$

In this equation, the parameter α represents the attenuation of the fiber. The loss is usually expressed in the units of dB/km i.e.,if the ratio $P_{out}/\ P_{in}$ when L is 1 km is α dB/km, then

$$10 \log_{10} \frac{P_{out}}{P_{in}} = -\alpha\, dB \tag{3.6}$$

Or

$$\alpha\, dB = (10 \log_{10} e)\alpha \approx 4.3143\alpha \tag{3.7}$$

The limit to the bandwidth in the current long-distance networks is the bandwidth of the erbium-doped fiber amplifiers that are widely deployed, rather than the bandwidth of silver [1].

Considering the most used bands today, the 1.3 and the 1.5 μm bands, over which the loss (in dB/km) is approximately in the factor of 2 of its minimum, has a usable bandwidth of about 80 nm at 1.3 μm and 180 nm at 1.55 μm. These bandwidths correspond to 35 000 GHz in optical frequencies which is an enormous amount of bandwidth.

The absorption peaks due to water vapor were virtually eliminated when Lucent introduced the AllWave single-mode optical fiber. This fiber, which is useful where there are no erbium-doped fiber amplifiers, has an even larger bandwidth.

Radiation losses: When rays propagate between the interface of two dielectric materials of different properties, radiation losses occur.

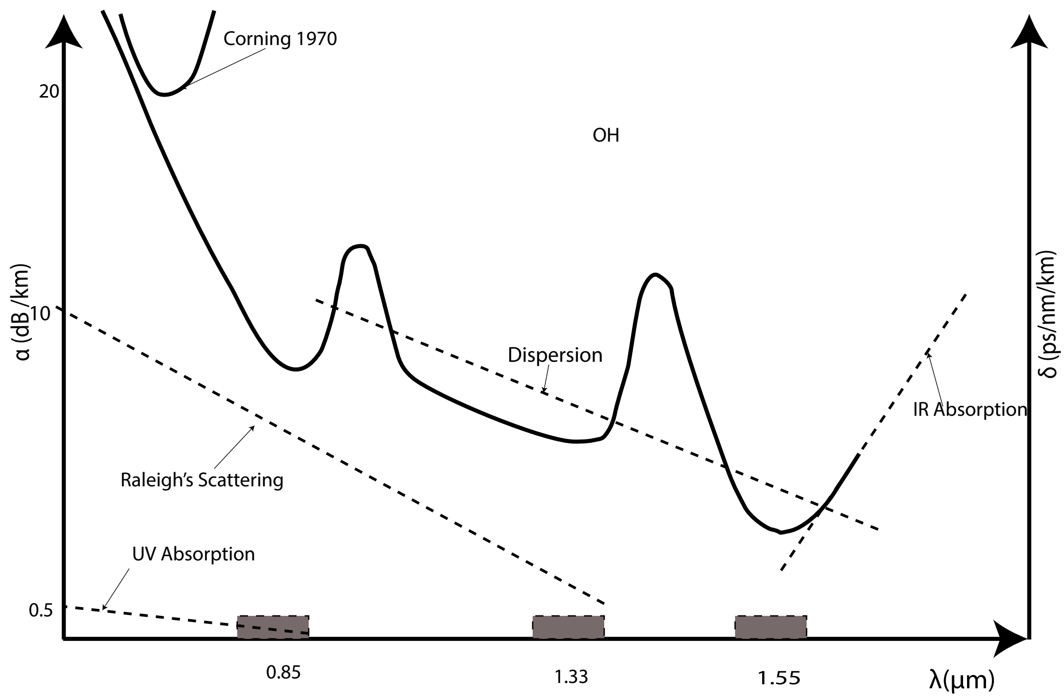

Fig. 3.9: Attenuation in fiber light-guides

3.6 Limitation of bit rate to distance

Due to the difference in the lengths of the paths taken by different guided rays, the energy in a narrow (in time) pulse at the input will be spread out over a larger time interval at the output of the fiber. This is known as *inter modal dispersion*, and its measure is obtained by taking the difference in time, δT, between the slowest and the fastest guided ray. Inter modal dispersion can be reduced by using *graded index* fibers, or even eliminated (single mode fiber).

The approximate measure of intermodal dispersion can be expressed as

$$\delta T = T_s - T_f = \frac{Ln_1^2}{cn_2}\Delta \tag{3.8}$$

where;
L = length of the fiber
T_f = time taken for the fastest ray of light to travel through the center of the core of the fiber and it takes
$T_f = Ln_1/c$ to traverse the fiber, T_s = time taken for the slowest ray of light to travel through the center of the fiber. The slowest ray is incident at the critical angle and it takes

$T_s = Ln_1^2/cn_2$ to propagate through the fiber,
c = speed of light in vacuum.

Intermodal dispersion limits the bit rate. A delay of δT that can be tolerated at a bit rate of B b/s is half the period of $1/2B$ s. This sets the limit of bit rate by intermodal dispersion as [1];

$$\delta < \frac{1}{2B} \tag{3.9}$$

The *bit rate-distance product* is the frequent measure of the capacity of an optical communication system. A system has a bit rate of xy (Mb/s)-km if it is capable of transmitting x Mb/s over a distance of y km. This device is also capable of transmitting at a less bit rate and shorter distances. This is no longer true for systems that are limited by nonlinear effects and chromatic dispersions. the bit rate-distance product of an optical link is constrained by intermodal dispersion (from equation3.9) to

$$BL < \frac{1}{2}\frac{n_2}{n_1^2}\frac{c}{\Delta} \tag{3.10}$$

In order to minimize the effect of intermodal dispersion, the value of Δ is chosen to be less than 1%. This is normally done using lenses and other mechanisms to couple light into the fiber since Δ is usually very small.

Minimizing Intermodal Dispersion: Graded-Index Multimode Fiber

Multimode fibers usually have *graded-index profiles* to reduce the effect of intermodal dispersion. In this design, the refractive index decreases from its maximum at the center of the core, to the cladding at the core-cladding interface.

3.7 Characteristics

Waveband	**Name**	**Range**[nm]
O	Original	1260-1360
O	Extended	1360-1460
S	Short	1460-1530
C	Conventional	1530-1565
L	Long	1565-1625
U	Ultra-long	1625-1675

Tab. 3.3: Individual wavebands of single-mode optical fibers [17].

3.8 Crosstalk in optical fibers

As a result of the savings they provide in the cost of installing and upgrading optical-fiber systems, wavelength multiplexing techniques are becoming more and more important to optical-fiber system designers [27]. Wavelength division multiplexed systems introduce the problems of cross-talk in optical-fiber systems which causes a degradation in the sensitivity of digital receivers. Tables **??** and **??** show the losses due to crosstalk in their respective wavelengths. Table **??** summarizes the penalties incurred in symmetric diplex and duplex systems for each of the three designs in the table.

Crosstalk is a disturbance caused by the electric or magnetic fields of one telecommunication signal that affects the dignal of adjacent circuits. The phenomenon that causes this is called electromagnetic interference (EMI). Having multiple cores so tight together inside a cladding will inevitably cause crosstalk to become a crucial factor to have in consideration in MCF [22].

In this section, the nature of this degradation (or power penalty) will be described for symmetric two-channel WDM components and systems carrying digital PCM signals using direct detection. Further, the analysis will be extended into multichannel asymmetric systems which exhibit additional problems of unequal crosstalk levels and quantum efficiencies, different fiber attenuation, and increased shit noise due to presence od many interfering channels.

There is always a tradeoff between the signal-to-noise ratio (SNR) and the crosstalk ratio in any transmission system, generally speaking [27].

3.8.1 Crosstalk mechanism

Looking at linear crosstalk in WDM systems. Crosstalks are produced due to the inability of a wavelength demultiplexer to prevent some power at the wrong wavelength from striking the photodetector [27]. Demultiplexors that employ interference filters have a poor blocking or rejection at these wavelengths. There are two defects in demultiplexers that employ diffraction grating[27]:

a. light is caused to be scattered by imperfections in the grating to the wrong output fiber output,
b. light can also be caused to be coupled into the wring output fiber by image spreading which results from angular dispersion of different wavelengths present in the source spectrum.

The portion of Rayleigh scattered light that returns directly to the source, ***backscatter***, causes interference. This phenomenon will not be discussed into details. This small proportion of reflected light is measured using OTDR (optical time-domain reflectometer) and it s typically in less than one millionth (<0.000001 percent or < -79 dB) [28].

Nonlinear mechanisms in the optical fiber which can cause coupling of power from one wavelength to another, such as Simulated Raman Scattering are dealt with in Section. 3.9.

Crosstalk can be defined as in Equation 3.11 below

$$XT(Z) = 10 \cdot \log_{10} \frac{P'(Z)}{P(Z)} [dB][22] \tag{3.11}$$

where $P'(Z)$ is the power at the output of the reference core and $P(Z)$ is the power at the output of the interference core(s). According to [27], it is far more useful to define crosstalk in symmetric systems in relation to the minimum detectable power MDP of the receiver, rather than to the actual signal power received, i.e.,

$$C = 10 \cdot \log_{10} \frac{I}{MDP} [dB][27] \tag{3.12}$$

and

$$x = \frac{I}{MDP} \tag{3.13}$$

where C is crosstalk value, I is the interference power and MDP is the minimum detectable power. This equation is essentially the same as Equation 3.11.

As digital systems require a specific eye opening (a voltage difference) for their operation, rather than a voltage or power ratio, this makes S/I to not be a useful quantity for predicting the power penalty [27].

For completely symmetric channels, it was shown that $C = R + M$ in diplex systems and $C = R + L + M$ in duplex systems, where R is the optical rejection or isolation, M is the system margin, and L us the loss of the link (including multiplexer and demultiplexer losses) [27].

However, for asymmetric systems, the definition of crosstalk must take into account the different quantum efficiencies at each wavelength (far apart wavelengths such as 850/1300 nm and 1300/1550 nm can be multiplexed together). In this case, crosstalk is defined in terms of voltage ratios x_{ij} at the decision circuit of the regenerator, that is, interfering voltage to minimum detectable signal voltage for a given error rate such as

$$x_{ij} = \frac{\eta_{ij} \cdot \lambda_j \cdot I_{ij}}{\eta_{ii} \cdot \lambda_i \cdot MDP} \tag{3.14}$$

where η_{ij} is the quantum efficiency in channel i at wavelength λ_i of channel j, and I_{ij} is the interfering power coupled into channel i from channel j. A more general definition of crosstalk in each channel is thus provided such that, from Equation 3.12 and 3.14,

$$C_{ij} = 10 \cdot \log_{10} \frac{I_{ij}}{MDP_i} \tag{3.15}$$

thus

$$C_{ij} = 10 \cdot \log_{10} x_{ij} - 10 \cdot \log_{10} \left(\frac{\eta_{ij} \cdot \lambda_j}{\eta_{ii} \cdot \lambda_i} \right) [27] \tag{3.16}$$

Expressing Equation 3.16 in terms of measurable parameters of WDM components and systems, the following equation is obtained

$$C_{ij} = 10 \cdot \log_{10} \left(\frac{MDP_j}{MDP_i} \right) + R_{ij} + M_j + (L_j)[27] \tag{3.17}$$

where R_{ij} is the optical rejection or isolation from channel j into channel i, and L_j (the fiber loss at λ_j) is included for special cases of duplex operation.

3.8.2 Model for restoring the eye opening

When creating a model to restore eye opening, it can be assumed by the model employed that the error rate in the presence of crosstalk can be recovered by restoring the original eye opening at the decision circuit of the regenerator [27].

The error rate in digital, optical systems is determined by the levels of the "0" and "1" states and the associated noise distribution with these levels, for example thermal noise etc. from the detector and amplifier, and quantum noise associated with the optical signal [27]

For small number of interfering channels, the interfering signal whose wave form is known (deterministic) can be considered to produce a shift in the "0" and "1" voltage levels, proportional to the interfering optical power. To restore the eye opening then, the received optical power is increased by an amount equal to the interfering optical power level (the voltage levels at the decision gate of the regenerator are a linear function of the reveived optical signal power in the case of optical systems that employ direct detection) [27].

The effect of restoring the eye opening in symmetric systems is therefore to increase the minimum detecrtable power required at the receiver for the same error rate to a new MDP', such that

$$MDP' - I' = MDP[27] \tag{3.18}$$

where I' is the new level of interfering, if changed by restoring the eye opening.

In the case of multichannel asymmetric systems, the interfering voltage in the channel i depends on all the quantum efficiencies of the detector at the other wavelengths. The eye opening is restored when

$$MDP_i' - \sum_{j=1}^{N} \frac{\eta_{ij} \cdot \lambda_j}{\eta_{ii} \cdot \lambda_i} = MDP_i, i \neq j \tag{3.19}$$

The power penalty in channel i in both cases is defined as

$$10 \cdot \log_{10} P_i \, \mathrm{dB.}, \text{ where } P_i = \frac{MDP_i'}{MDP_i}$$

The values of P_i for different design options are summarized in the Tab. **??**.

Crosstalk elimination in multicore fibers

Crosstalk can be the main limitation to the capacity of transmission in terms of signal quality and quantities of cores that that are managed inside a multicore fiber. It is necessary to use accurate methods to estimate crosstalk in multicore fibers. Therte are two methods which have been developed to estimate crosstalk in MCF (sec 3.2); the Coupled-Mode Theory (CMT) and the Coupled-Power Theory (CPT) [22].

- **Coupled-Mode Theory**

  Coupled mode theory (CMT) is a perturbational approach for analysing the coupling of vibrational systems (mechanical, optical, electrical, etc.) in space or in time[22]. When two waveguides are in close proximity, they become coupled and exchange power as a function of z. This, very often, leads to periodic exchange of power between the waveguides.

  Pertubation Analysis: Assumption To make the analysis simpler, it is assumed that the supermodes can be represented as a weighed sum of the individual guided modes. This implies that, on the introduction of the second guide sufficiently close enough to the first one, the modes do not change at all (which in reality is not true because the modes are slightly deformed, but are still coupled) [3]

  If two waveguides are sufficiently close then the optical modes of each waveguide either interfere or couple with each other, also if the electromagnetic field distributions after mode coupling are not so different than before the coupling, then the propagation characteristics of the coupled waveguides can be analysed utilizing CMT [22].

  For a bent MCF, the conventional coupled-mode equation (CME) without higher-order terms is shown in the equation 3.20 below.

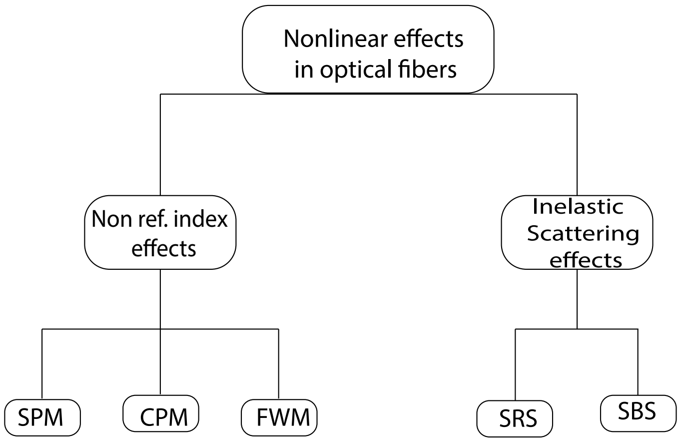

Fig. 3.10: Nonlinear effects in optical fibbers [7].

$$\frac{dA_m}{dz} = j \sum_{n \neq m} \kappa_{min} A_n(z) \exp(j\Delta\beta_{min} z) f(z)[22]. \tag{3.20}$$

where A_m is the mode amplitude in the core m, z is the direction of propagation, κ_{min} is the mode-coupling coefficient (MCC) from core n to m, $\Delta\beta_{mn} = \beta_m - \beta_n = -\Delta\beta_{nm}$ is the propagation constant difference with β_m and β_n being the propagation constant of modes in core m and core n and f is the phase function describing the bending and twisting effects along the fiber. The phase function is formed by two parts; one is deterministic ($\exp[j(\phi_m - \phi_n)]$) and the other is the random part ($f(z) = \exp[j(\phi_m - \phi_n)]\delta f(z)$) [22].

3.9 Nonlinear Effects in Optical Fibers

The term nonlinear in optics means intensity independent phenomenon. Non linear effects, Fig. 3.10[7], occur due to

- change in the refractive index of the medium with optical intensity and,
- inelastic scattering phenomenon

The *Kerr-effect* is as a result of the power dependence of refractive index. The Kerr-effect is also known as *quadratic electro-optic (QEO) effect* is a change in the refractive index of a material in response to an applied electric field. The Karr-nonlinearity manifests itself in three different effects depending on the type of input signal: Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM). The inelastic scattering phenomenon can induce stimulated effects such as Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS) at higher power levels [7].

Any dielectric medium behaves like a nonlinear medium for intense electromagnetic fields. The origin of nonlinearity fundamentally lies in anharmonic motion of bound electrons under the influence of an applied field. The total polarization P induced by electric dipoles is not linear due to this anharmonic motion but satisfies the more general relation as

$$P = \epsilon X_0 E^{(1)} + \epsilon_0 X^{(2)} E^2 + \epsilon X_0^3 E^{(3)} + \epsilon_0 X^{(4)} E^4 + \dots \qquad (3.21)$$

where ϵ_0 is the permittivity of free space or vacuum and $E^{(k)}(k = 1, 2, \dots)$ is the order of susceptibility.

A medium, that lacks inversion symmetry at the molecular level, has a non-zero second order susceptibility. For s symmetric molecule like silica however, the X^2 disappears. Therefore, the dominant contribution to P is provided by linear susceptibility $X^(1)$, and the second order susceptibility is responsible for second harmonic generation and sum-frequency generation [7].

As a result of symmetric molecules, optical fibers do not exhibit second order nonlinear refractive effects, however, the electric quadruple and magnetic-dipole moments can generate a weak second order nonlinear effects. Therefore, the lowest-order nonlinear effects in fibers is as a result of the third order susceptibility, $X^(3)$[7].

The magnitude of nonlinear effect is affected by the following:

- **effective susceptibility and effective refractive index:**
  The change in refractive index is usually small and is directly proportional to the length of the optical fiber. Its expression can be simplified as

  $$n_{eff} = n_l + \frac{3}{4}\frac{X^{(3}}{c\epsilon_0 n_l^2} I or, n_e f f = n_l + n_{nl} I \qquad (3.22)$$

  Thus,

  $$\Delta n = n_{nl} I \qquad (3.23)$$

  where n_{nl} is the nonlinear refractive index and I is the optical intensity. In addition to the Kerr effect which is a purely electronic nonlinearity, *electrostriction* can significantly contribute to the value of nonlinear index. he electric field of light causes density variations (acoustic waves) which themselves influence the refractive index via the photoelastic effect. That mechanism, however, occurs on a much longer time scale and is thus relevant only for relatively slow power modulations, but not for ultrashort pulses [29]
  Higher order terms are negligible and hence neglected. Due to long interaction as a result of long optical cable (10 - 10,000 km) the accumulated nonlinear effect becomes significant. This nonlinear term is responsible for the formation of solitons.

Fused silica, as used for optical fibers for example, has nonlinear index of $\approx 3\times10^{-16}\,\mathrm{cm^2W^{-1}}$. This value can be much higher for soft glasses particularly for semiconductors because it depends strongly on the bandgap energy [29]. It is also good to note that, one intensive beam causes twice as large refractive index increase for other beams according to the equation 3.23, assuming that both beams are in the same polarization plane.
There may be no further increase in proportion to the intensity at extremely high optical intensities, but a saturation and even a substantial and decrease of refractive index. Raman Scattering, a nonlinear polarization with delayed response is not considered to be part of Kerl effect. It can not simply be described as modification of refractive index.
Also, it is good to note that, the effective refractive index increases caused by some intense beam for other beam is twice as large as that according to the equation shown above, assuming both beams are in the same polarization plane.

- **Effective transmission length:**
As already mentioned above, the transmission length affects nonlinear effects. When the fiber link is long, light has more interaction resulting is a greater nonlinear effect. The effective length L_{eff} is the length up to which power is assumed to be constant. As optical power propagates along a fiber link, its power at any point, z, from the power input can be expressed by the equation:

$$P_z = P_{in}\exp^{-\alpha z} \tag{3.24}$$

where P_{in} is the input power (that is, power when $z = 0$), α is the coefficient of attenuation.

$$P_{in}L_{eff} = \int_{z=0}^{L} P(z)\,dz \tag{3.25}$$

Using equations 3.24 and 3.25, effective link length is obtained as,

$$L_{eff} = \frac{1-\exp^{(-\alpha z)}}{\alpha} \tag{3.26}$$

- **Effective Cross-sectional Area**
The intensity in fiber is inversely proportional to the area of the core and the effect of nonlinearity grows with intensity in fiber. It is reasonable to use effective cross-sectional area, A_{eff}, of the fiber since power is not uniformly distributed within the cross-section. Equation 3.27 shows the relationship between A_{eff} and the actual area $A(r,\theta)$:

$$A_{eff} = \left[\frac{\int_r\int_\theta rdrd\theta I(r,\theta)}{\int_r\int_\theta rdrdI^2\theta(r,\theta)}\right] \tag{3.27}$$

where r and θ denotes the polar coordinates.

3.9.1 Self-Phase Modulation

The less intensity portions of an optical pulse encounter a lower refractive index of the fiber compared with the higher intensity portions as it travels through the fiber. In a medium that has an intensity-dependent refractive index, time varying signal intensity in facts produces time varying refractive index. The leading edge experiences a positive refractive index gradient dn/dt and the trailing edge a negative refractive index gradient $-dn/dt$. As a result of this temporally varying index, a temporally varying phase change is produced as shown in Fig. 3.11.

There is broadening of the spectrum without any change in the temporal distribution in SFM. In case of dispersion, the pulse broadens in time domain while the spectral content is unaltered. Thus, SPM by itself leads to chirping, regardless of the pulse shape and, broadening of the pulse is as a result of dispersion [7].

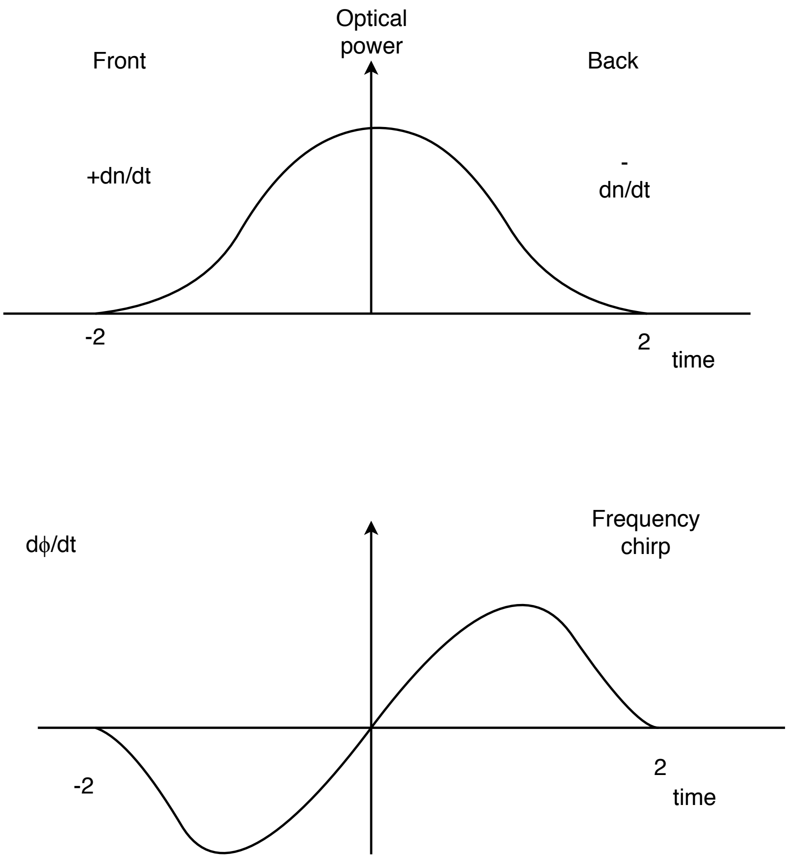

Fig. 3.11: Phenomenological description of spectral broadening of pulse due to SPM [7].

As different parts of the pulse undergo different pulse shift due to intensity dependence of phase fluctuations, frequency chirping results where the rising edge of the pulse finds frequency shift in the upper side and the trailing edge in the lower side. The effect of SPM, therefore, is to broaden the spectrum of the pulse, keeping the temporal shape the same. This effect is mostly experienced in system with high-transmitted power as the chirp effect is proportional to the transmitted signal power [7].

Equation 3.28 expresses the phase, ϕ, introduced by a field, E, over a fiber of length, L, of an optical fiber.

$$\phi = \frac{2\pi}{\lambda} nL \tag{3.28}$$

where λ is the wavelength of the optical pulse propagating in fiber of refractive index n, and nL is known as the path length.

Application of SPM Phenomenon

Solitons and pulse compression are two important applications of SPM concept.

- **Solitons:**
  Soliton pulses do not broaden during propagation as a result it has tremendous potential for application in super high bandwidth optical systems. Chirping caused by SPM has lower frequencies in the leading edge and higher frequencies in the trailing edge. On the other hand, the chirping as a result of linear dispersion, in the wavelength region above zero dispersion wavelength, is associated with higher frequencies in the leading edge and lower frequencies in the trailing edge. As these effects are opposite, they can compensate each other by proper choice of pulse shape (a hydraulic secant-shape). This results in the pulse propagation without distortion by mutual compensation of dispersion and SPM [7].

- **Optically Tunable Delays:** The transmission data rate in ultra-high speed optical communications is limited by the optical/electrical conversion of information. As a result, it is desirable to have all-optical components in for buffering and delaying signal pulses.A novel technique which involves spectral broadening vis SPM and wavelength filtering [7]

- **Pulse Compression:**
  The red-shifted leading edge of a pulse in the wavelength region where chromatic dispersion is positive travels slower and moves towards the center of the pulse. In the same way, tje blue shifted trailing edge travels faster, and

moves towards the edge of the pulse. This causes the pulse to narrow. Another scheme for pulse compression is based on filtering self-phase modulation-broadened spectrum [7].

- **Optical 40 Gbps 3R Regenerator**
  All optical 3R utilizes combined effect of SPM and cross-absorption modulation. Experimentally verified, the performance of such regenerators is for 40 Gbps data rate. The chromatic dispersion tolerance is enhanced by the introduction of a pre-distortion block configuration including a non-linear fiber.

3.9.2 Cross Phase Modulation

The effect of SPM non linear effect is a major limitation in single channel systems. Another nonlinear effect called Cross Phase Modulation (CPM) results from the intensity dependence of refractive index. The CPM is always accompanied by a SPM and occurs because the nonlinear refractive index of an optical fiber can seen by an optical beam depends not only on the intensity of that beam but also the intensity of other co-propagating beams. This results when two or more pulses propagate simultaneously [7].

3.9.3 Four Wave Mixing

Four Wave Mixing (FWM) arises from the non-linear response of bound electrons of a material to an applied optical field. The polarization induced in the medium in fact contains not only linear terms but also the non-linear terms. Non linear susceptibilities of different orders govern the magnitude of these terms. The FWM process originates from third order non-linear susceptibility ($X^{(3)}$)[7].

If three optical fields with carrier frequencies ω_1, ω_2 and ω_3 simultaneously co-propagate inside the fiber, a fourth frequency ω_4 is generated by ($X^{(3)}$), which is related by a relation

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3 \tag{3.29}$$

FWM occur when photons are created when one or move waves are annihilated and new photons are created at different frequencies such that the net energy and momentum are conserved during the interaction [7].

Unlike SPM and CPM which are significant mainly for high bit rate systems, the effect of FWM is independent of the bitrate and us critically dependent on the channel spacing and fiber dispersion. Decreasing the dispersion increases the FWM effect and so does decreasing the channel spacing [7].

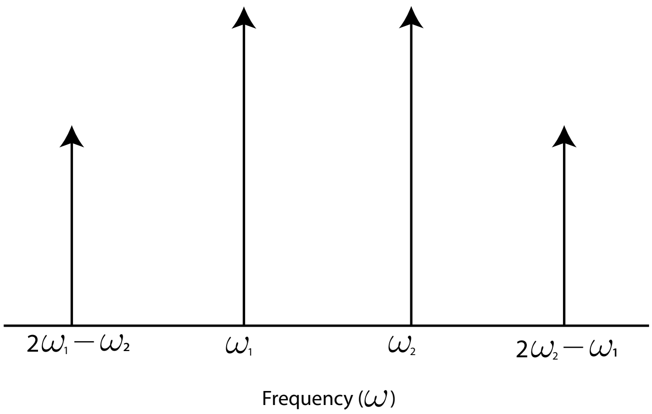

Fig. 3.12: Showing mixing of two waves [7].

Considering a a WDM signal which is sum of n monochromatic planes, the electric field of such signal can be written as

$$E = \sum_{p=1}^{n} E_p \cos(\omega_p t - k_p z) \tag{3.30}$$

Then the nonlinear polarization is given by

$$P_{nl} = \epsilon_0 X^{(3)} E^3 \tag{3.31}$$

For this case, $P_(nl)$ takes the form as

$$P_{nl} = \epsilon_0 X^{(3)} \sum_{p=1}^{n} \sum_{q=1}^{n} \sum_{r=1}^{n} E_p \cos(\omega_p t - k_p z) E_q \cos(\omega_q t - t_q z) E_r \cos(\omega_r t - k_r z) \tag{3.32}$$

Equation 3.32 could be expanded to give terms that represent the effect of Self-Phase Modulation (SPM) and Cross Phase Modulation (CFM). Certain terms could be neglected due to phase mismatch thus contribute little. The other term represent the phenomenon of four-wave mixing. In this phenomenon, three EM waves that propagate in a fiber generate new waves with frequencies $(\omega_p \pm \omega_q \pm \omega_r)$. This is analogous to intermodulation distortion in electrical systems.

In general terms,

$$\omega_{pqr} = \omega_p + \omega_q - \omega_r \quad \text{with } \ p, q \neq r \tag{3.33}$$

Mixing of two waves at frequencies ω_1 and ω_2 is shown in Fig. 3.12. In this simple example, the two waves generate sidebands at $(2\omega_1 - \omega_2)$ and $(2\omega_2 - \omega_1)$. In a similar way, when three copropagating waves mix, they create nine new optical sidebands waves at frequencies given by Eqn. 3.29. As these sidebands travel along with original waves, they continue to grow at the expense of signal-strength depletion.

3.9.4 Nonlinear Scattering effects

The nonlinear scattering effects in optical fiber occur due to inelastic-scattering pf photon to a lower energy photon. The energy difference is absorbed by the molecular vibrations of phonons in the medium. This phenomenon can be described as transfer of light wave energy to another wave, which is at a higher wavelength, (lower energy), such that the energy difference appears in form of phonons. Such wave is known as Stokes wave [8].

The two nonlinear scattering phenomenon in optical fibers are related to vibrational excitation modes of silica. They are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The fundamental difference between the two is that, the optical phonons participate in SRS while SBS is throufh acoustic phonons [8]. SRS can occur in both directions while SBS occurs only in one direction (backwards).

These processes cause disproportionate attenuation at high optical power levels and also causes transfer of power from one mode to another. It also provide optical gain but with a shift in frequency.

Stimulated Brillouin Scattering

This process occurs in optical fiber at large intensity. Compression (due to electric field also known as pump) is produced by the large intensity in the core of the fiber through the process known as electrostriction [8] which produces density fluctuation in the fiber medium increasing the medium disorder which in turn modulated the linear refractive index. This results in an electrostrictive-nonlinearity [30]. The modulated refractive index behaves as an index grating which is pump-induced. Brillouin scattering is the scattering of the pump light through Bragg diffraction by pump induced index grating [8].

- **Physical Process**
  The electrostriction process produces a macroscopic acoustic wave at some frequency ω_B for an oscillating electric field at the pump frequency ω_P. The Brillouin scattering may be spontaneous or stimulated. There is annihilation of a pump photon in spontaneous Brillouin scattering, which results in simultaneous creation of a Stoke and an acoustic photon. In such scattering, the law of conservation of energy and momentum must be followed [8].

The Stoke shift ω_B must be equal to (ω_P - ω_S), for energy conservation. The momentum conservation requires $\mathbf{k}_A = (\mathbf{k}_P - \mathbf{k}_S)$, where $\mathbf{k}_A$, $\mathbf{k}_P$ and $\mathbf{k}_S$ are momentum vectors of acoustic, pump and Stoke waves respectively.

- **Threshold Power**

The interaction between pump and Stokes wave taken into consideration, the initial growth of Stokes wave under CW and quasi-CW condition can be written as

$$\frac{dI_S}{dz} = g_B I_P IS[7] \tag{3.34}$$

where g_B is Brillouin gain coefficient, I_P and I_S are the pump and Stokes wave intensities respectively.

Photons are produced within the bandwidth of Brillouin-gain spectrum by the Brillouin scattering and hence all frequency components will be amplified. The frequency component for which g_B is maximum builds up almost exponentially. Equation 3.34 can be written, considering the fiber losses at Stokes frequency and counterpropagating nature of Stokes wave, as

$$\frac{dI_S}{dz} = -g_B I_P I_S + \alpha_S I_S[7] \tag{3.35}$$

For pump wave coupled equation can be given as

$$\frac{dI_P}{dz} = -\frac{\omega_P}{\omega_S} g_B I_P IS - \alpha_S I_S[7] \tag{3.36}$$

where α_P is responsible for fiber losses at pump frequency.

The two coupled equations 3.35 and 3.36 control the feedback process responsible for Brillouin scattering. Due to small Brillouin shift, one may consider for simplicity $\omega_P \approx \omega_S$ and thus $\alpha_P \approx \alpha_S \equiv \alpha$. Now these equations can be written as

$$\frac{dI_S}{dz} = -g_B I_P I_S + \alpha I_S[7] \tag{3.37}$$

and

$$\frac{dI_S}{dz} = -g_B I_P IS - \alpha I_S[7] \tag{3.38}$$

Without fiber, these equations simplify as $(I_S - I_P)$ = constant which describes the conservation phenomenon on light energy during Brillouin process.

The threshold power is a minimum power level at which the effect of nonlinearity starts [8]. It is incident power at which the pump and Stokes powers ae equal at the fiber output.

The threshold power can be approximately calculated from the equation 3.39

$$P_{th} \approx \frac{21bAeff}{g_B L_{eff}}[8]. \tag{3.39}$$

where A_{eff} is the effective core area of the fiber and $Leff$ is the effective length of the fiber. The value, b is that of polarization and it lies between 1 and 2 depending on relative polarization of the pump and Stoke wave.

- **Reduction in Power Penalty**

  An additional amount of power is needed at the receiver to maintain the BER in the absence of nonlinear effects, when any nonlinear effect contributes to signal impairment.

  Power penalty due to SBS can be reduced in many ways: [8]

  1. Keeping the power level per WDM channel much below the SBS threshold. One may have to reduce the amplifier spacing in long-haul systems.
  2. Increasing the linewidth of the source used can be used to decrease the effect of small gain bandwidth of SBS phenomenon.A significant dispersion penalty may result from this.
  3. The power present in the optical fiber may be reduced by using phase modulation method instead of amplitude modulation. Less power means reduction in the SBS penalty.

- **Application of SBS phenomenon**

  With suitable system arrangement, SBS, which normally puts limitations on optical communication systems, can be useful for making many optical devices briefly described below [8].

  1. Fiber sensors: Whenever there is a change in temperature or strain, the refractive index of silica changes in response to such vibrations. These changes produces change in Brillouin shift. The distribution of temperature and strain can be obtained by registering the changes in Brillouin shift.
  2. Brillouin Fiber Amplifiers: This utilizes the ooptical gain in SBS process in amplification of weak signal provided shift of weak signal from frequency is equal to Brillouin shift.
  3. Beam Combiner: This method may be useful in increasing the brighness of array of fiber amplifiers.
  4. Pulse Delaying and Advancement: SBS is helpful in controlling the group velocity of an optical pulse as it travels along fiber. Experimentally, the change in group index of 10-3 have been achieved.
  5. Pipeline Buckling Detection: In an energy pipe a distributed Brillouin fiber can be used to detect localized pine-wall buckling.

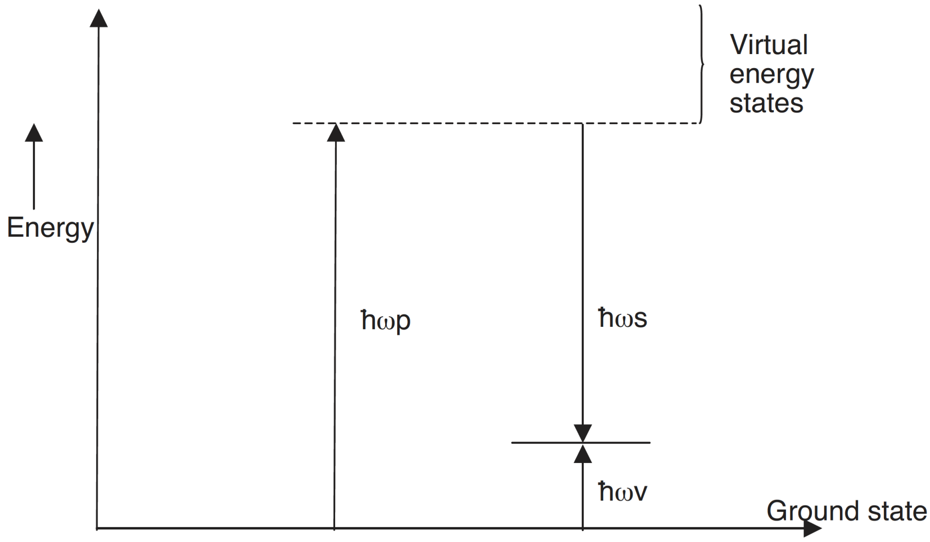

Fig. 3.13: Schematic representation of Raman scattering [8].

Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) is a four-photon process which leads to the transfer of energy from a pump wave to lower frequency (Stokes) waves and higher frequency (anti-Stokes) waves through the intemediary of an optical phonon in the transmission medium [31].

This effect is the elastic scattering of a photon with optical phonon originating from a finite response time of the third order nonlinear polarization of the material [8].Spontaneous SRS occurs when monochromatic light beam propagates in an optical fiber. It transfers some of the photons in new frequencies. Stock shift happens when the scattered photon lose energy (Fig. 3.14(a)) or anti-Stocks shift when it gains energy (Fig. 3.14(b)).

The polarization of scattered photons may be in the same (parallel scattering) or orthogonal (perpendicular scattering) if the pump beam is linearly polarized. The probability of scattering to other frequencies is enhanced if photons at those frequencies are already present. This process is known as stimulated Raman scattering [8]. The Raman amplifiers exploit the feature of Raman scattering where a coincident photon at the downshifted frequency receives a gain.

- **Basic Theory**
  Compared to Rayleight scattering, Raman scattering is a weak effect. It occurs due to slight modulation of the refractive index through molecular vibration of material [32]. When a photon of energy $\hbar\omega_P$ travels through a material, it

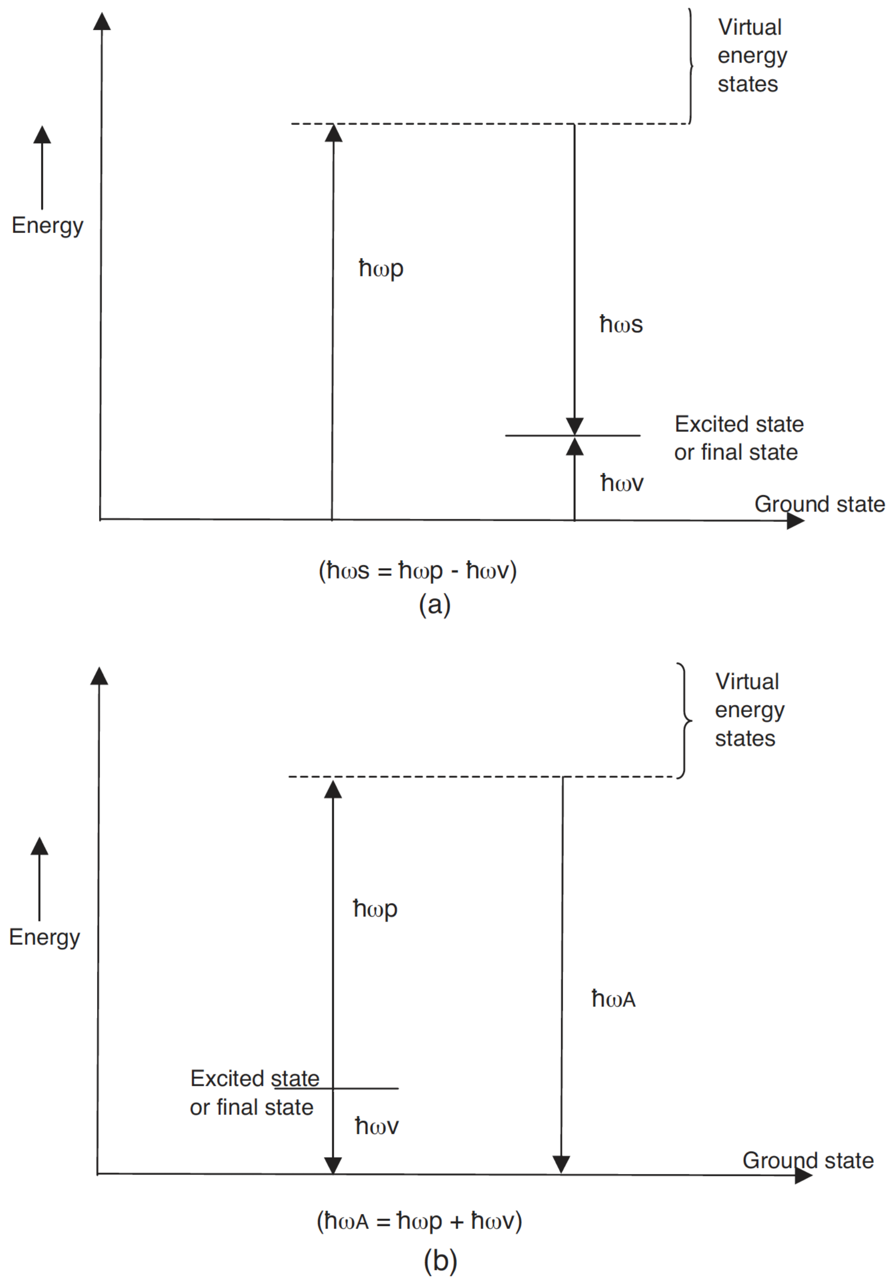

Fig. 3.14: (a) Stokes scattering process. (b) Anti-Stokes scattering process [8].

can excite a vibrational transition of the material forming an optical phonon with energy $\hbar\omega_V$ and a photon with slightly reduced energy, Fig. 3.13, $\hbar\omega_S$ such that:

$$\hbar\omega_S = \hbar\omega_P - \hbar\omega_V \text{ [8]}.$$

A dipole moment p is induced by the electric vector when a light wave with angular velocity ω is incident on the material, such that

$$p = \alpha E$$

where α is the molecular polrizability and E is the electric field vector. The α measures the resistance of the particle to the displacement of its electron cloud.
For harmonic electric field $E(t) = E_0 exp(j\omega_P t)$, the variation of α with time can be written as

$$\alpha(t) = \alpha_0 + \left(\frac{\partial\alpha}{\partial x}\right)_{x_0} dx(t) \tag{3.40}$$

where $dx(t)$ is the displacement from the equilibrium molecular lengh x_0 such that

$$dx(t) = dx_0 \exp[\pm j\omega_V t] \tag{3.41}$$

The polarization vector P is defined as dipole moment per unit volume. If there are N dipoles per unit volume then using equations 3.40 and 3.41

$$P(t) = N\alpha_0 E_0 \exp[j\omega_P t] + \left(\frac{\partial\alpha}{\partial x}\right)_{x_0} dx_0 N E_0 \exp[j(\omega_P \pm \omega_V)t][8]. \tag{3.42}$$

This equation (3.42) consists of a linear part which corresponds to linear optical phenomenon which remains unshifted. The second part is nonlinear as the output frequency is different from the input frequency.

- **The Raman Process**
  The Stoke Raman process is also known as the forward Raman process (Fig. 3.14(a)). Equation 3.43 shows the energy conservation process, where E_g and E_f are the ground and the final energy levels respectively.

$$E_g + \hbar = E_f + \hbar\omega_S \tag{3.43}$$

- **SRS Spectrum**
  The growth of stimulated Raman scattered intensity with classical electromagnetic concepts is proportional to the product of the pump and the signal intensity Equation 3.44

$$\frac{dI_S}{dz} = g_R I_P I_S[8] \tag{3.44}$$

where I_P and I_S are the pump intensity and the signal intensity respectively, and g_R is known as the Raman-gain coefficient.

- **Threshold Power**

  Equation 3.44 gives the initial growth in Stokes wave. Fiber losses taken into consideration, the net growth in Stokes wave is expressed as

$$\frac{dI_S}{dz} = g_R I_P I_S - \alpha_S I_S[8] \tag{3.45}$$

  where α_S is the attenuation coefficient.
  The coupled equation for pump wave can be written as

$$\frac{dI_P}{dz} = -\frac{\omega_P}{\omega_S} g_R I_P I_S - \alpha_P I_P[8] \tag{3.46}$$

  The two equations (Equation 3.45 and 3.46) are known as the coupled wave equations for forward Raman scattering. In the absence of fiber losses, these equations simplify to

$$\frac{d}{dz}\left(\frac{I_S}{\omega_S} + \frac{I_P}{\omega_P}\right) = 0 \tag{3.47}$$

  SRS practically builds up from spontaneous Raman scattering throughout the entire length of the fiber. The stimulation occurs in Raman process when pump power exceeds a certain power level known as the threshold power. The threshold power or forward SRS can be approximated as

$$P_{th} \approx \frac{16A_{eff}}{g_R L_{eff}} \tag{3.48}$$

  and for backward SRS as

$$P_{th} \approx \frac{20A_{eff}}{g_R L_{eff}} \tag{3.49}$$

  where A_{eff} is the effective cross sectional area and L_{eff} is the effective length. The forward SRS is reached first at a given power. The backward SRS is generally not observed in fibers.

- **Reduction in SRS Penalty**
  1. Signals in different channels travel at different velocities in the presence of dispersion and hence reducing the chances of overlap between pulses propagating at different wavelengths.
  2. Decreasing channel spacing reduces the SRS penalty

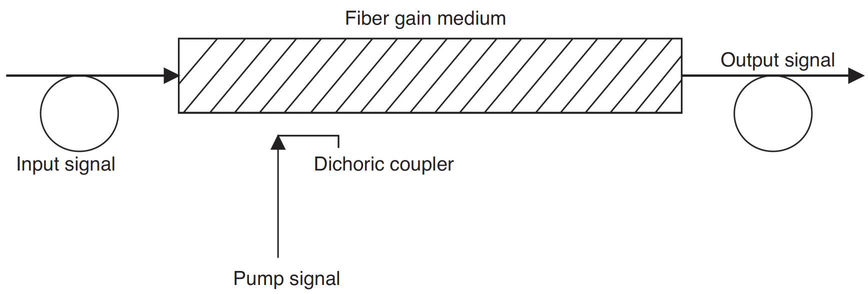

Fig. 3.15: Schematic of Raman fiber amplifier [8].

3. Keeping the power level below the threshold level. This requires reduction in distance between amplifiers

- **Applications of SRS Phenomenon**
  1. **Raman Fiber Laser** SRS phenomenon is used to develop fiber based Raman laser.
  2. **Raman Fiber Amplifier** Optical fiber amplification within optical fibers may be provided using SRS phenomenon. Energy is caused to be transferred from pump to signal by the SRS process. As long as the appropriate laser is available, the amplification can occur at any wavelength. Figure 3.15 shows a schematic of a Raman amplifier.
  3. **Eye-Safe Laser** Using a special s-polarized reflective resonator, a beam of an eye-safe laser with 31.8 mJ output energy and 2.0 ns pulse width can be obtained. Fundamentally, the eye-safe laser uses SRS.

4 NEW TECHNOLOGIES IN OPTICAL FIBER

Optical fibers are used in high-speed data transfer services, in both short- and long-range communications. Combined with the added surge in cloud-based applications, audio-video services, and video-on-demand technology, the market shows no signs of slowing.

The primary focus over the past 10 or so years has been on developing higher spectral efficiency optical data signals for transmission on existing fiber infrastructure, known as digital coherent transmission.

Optical transmission data rates have been steadily increasing since the birth of the industry in the 1980s. Where early transmission speeds were measured in Mb/s, today's single wavelength transceivers run at 200 Gb/s, which, within a dense wavelength division multiplexing (WDM) system, enables the transmission of multiple Tb/s per fiber.

4.1 New Emerging Fiber Products

4.1.1 Fiber optic HDMI

There is an increasing demand in the residential market which has driven the development of a new era of cable building. HDMI 2.0, also referred to as HDMI UHD was released in 2013 with a maximum bandwidth of 18.0 Gbps. There is eventually another HDMI version, HDMI 2.1 which supports resolutions up to 10K and a bandwidth improvement from 18.0 Gbps to 48 Gbps [33]

With copper, the requirements to build a collapsed High-Speed connectivity (video/audio) and low latency Low Speed analogue signals [it reads as digital] has to be looked at, as well as maintaining correct voltage the entire path. This is more difficult in the development stages than with optical, which in theory simply involves finding the TX/RX set that will match the speed needed. In practical however, it is more complicated.

As roughly general rules, it is considerable to use copper cables for distances up to 25 feet (about 8 meters). Fiber optics would be preferable for longer distances [34].

4.1.2 Multiwavelength Multimode fiber

Multiwavelength multimode fiber might be designed to accommodate four channels, each about 20 or 30 nm apart. The spacing will be such as to make possible the use of low-cost transceivers. To preserve backward compatibility, the likely wavelengths will start at 850 and then move upward out to about 1000 nm [35]

Multiwavelength multimode fiber (Early investigators of multimode fiber designs recognized that a parabolic refractive index profile in the core substantially reduced the intermodal dispersion in the fiber)

4.1.3 Multicore fibers

The other hot topic in the industry, he added, involves fibers with multiple cores, as that represents another way to increase bandwidth. Issues here involve the fiber connectors and how to splice the fiber. The challenge is that these multiple fibers have cores about the size of a human hair. All have to be connected, eventually and economically, to a transceiver.

4.1.4 Large diameter fibers

Part of the solution involves changes to the fiber. In the past, standard single-mode fiber used in long-haul communication had effective light confining core of about $80\,\mu m^2$. Fibers now are being manufactured with cores of $125\,\mu m^2$ for terrestrial use and up to $150\,\mu m^2$ for submarine fibers. These large-area fibers that are currently being deployed are used to optimize the cable for coherent modulation formats, which makes 100 Gbps and 400 Gbps possible [35]

The large-diameter fibers offer a high nonlinear threshold and higher dispersion coefficient making them better for coherent modulation.

4.1.5 MicroCore fiber

Another innovation that can help ease the bandwidth crunch in data centers is the use of what AFL [1] calls MicroCore fiber. Since data-center fiber will be inside a building and encased in a tray, it does not need a bulky protective covering. Eliminating that covering reduces the size of a cable as much as 75 percent and cuts installation cost. Approaches like this can be combined with wavelength multiplexing to create a solution to growing bandwidth demands.

[1] https://www.aflglobal.com

4.2 Emerging Fiber Technologies

4.2.1 Quantum Key Distribution

A Quantum Key Distribution, QKD, system consists of a quantum channel and a classical channel. The quantum channel is only used to transmit Qubits (single photons) and must consist of a transparent optical path. It is a lossy and probabilistic channel.

QKD is a technology, based on the quantum laws of physics, rather than the assumed computational complexity of mathematical problems, to generate and distribute provably secure cipher keys over unsecured channels. It does this by using single photon technology and can detect potential eavesdropping via the quantum bit error rates of the quantum channel [9].

QKD, is a kind of quantum encryption in which a secret password is shared between two distant parties. The secret password (key) is distributed as bits of data. If an eavesdropper (man in the middle) tries to intercept the message, the bits will be disturbed and the parties will know that the transmission has been intercepted. If undisturbed, the key can be used to encode messages that are sent over an insecure channel.

Fig. 3.27 shows the basic scenario of Quantum Key Distribution Protocols, QKDPs. In this proposed QKDPs, the participants and the Trusted Center, TC, synchronize their polarization bases according to a preshared secret key. The preshared secret key together with a random string are used to produce another key encryption to encipher the session key, this is performed during the session key distribution [9].

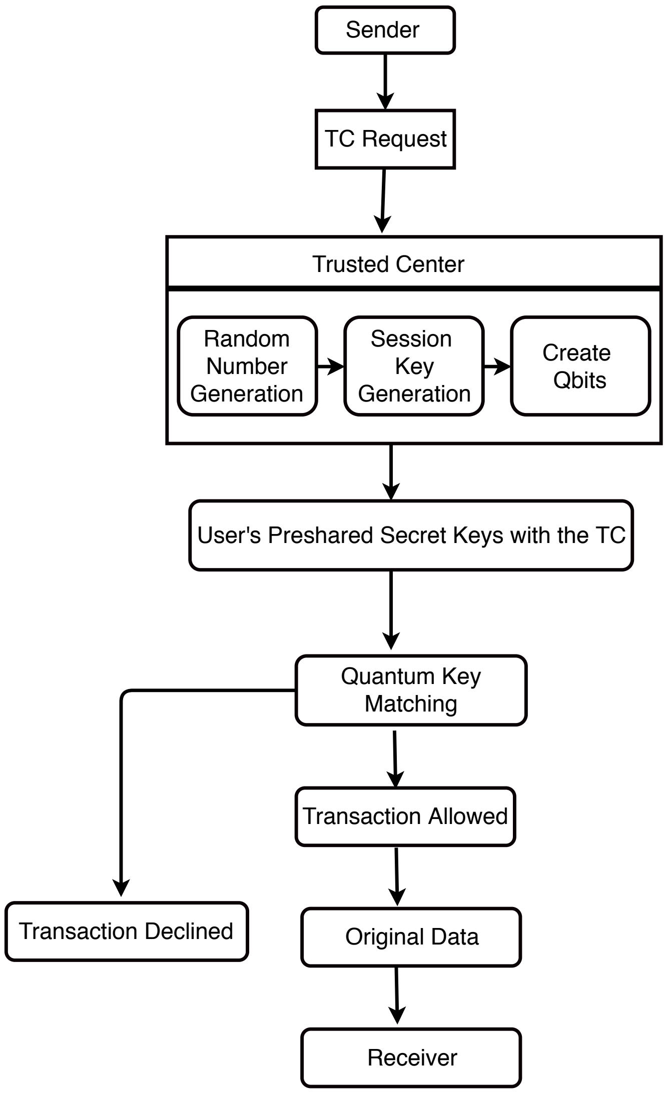

Fig. 4.1: System architecture of QKD [9].

5 MODULATION FORMATS

Many advantages are brought by digital communication over analogue, which can be represented in many features, as easy storage and faster processing. Using optical fibers, the transmission fidelity can be improved [13]. In this chapter, different modulation formats used in optical communication will be discussed and compared. The common modulation formats are the Return-to-Zero (RZ) and Non Return-to-Zero (NRZ). Other techniques include duo-binary, modified duo-binary, carrier-suppressed RZ (CSRZ), Differential Phase Shift Keying (DPSK) and Differential Quadrature PSK (DQPSK) formats.

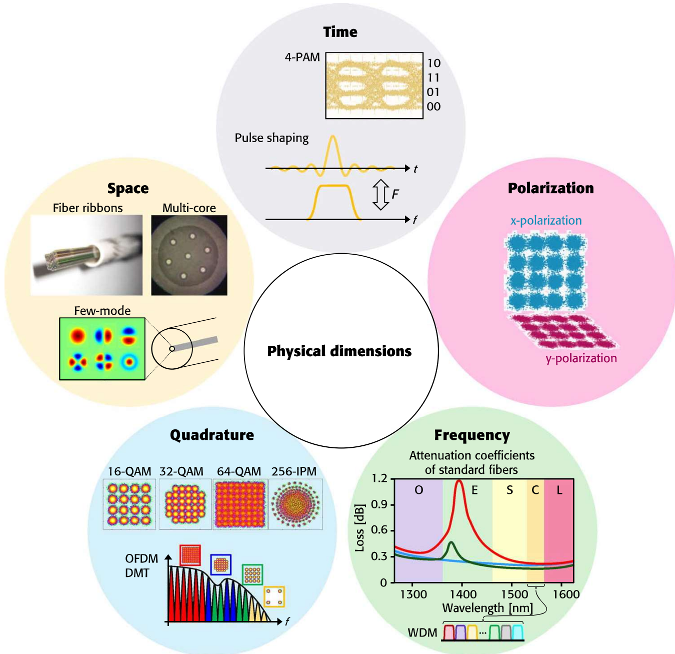

Fig. 5.1: Physical dimensions for modulation and multiplexing of electromagnetic waves [10].

5.1 PHASE SHIFT KEYING

Discrete variation in a carrier's amplitude or frequency can be used as a way of representing binary information (ones and zeros). Digital data can also be represented can also be represented using phase; this technique is called Phase Shift Keying.

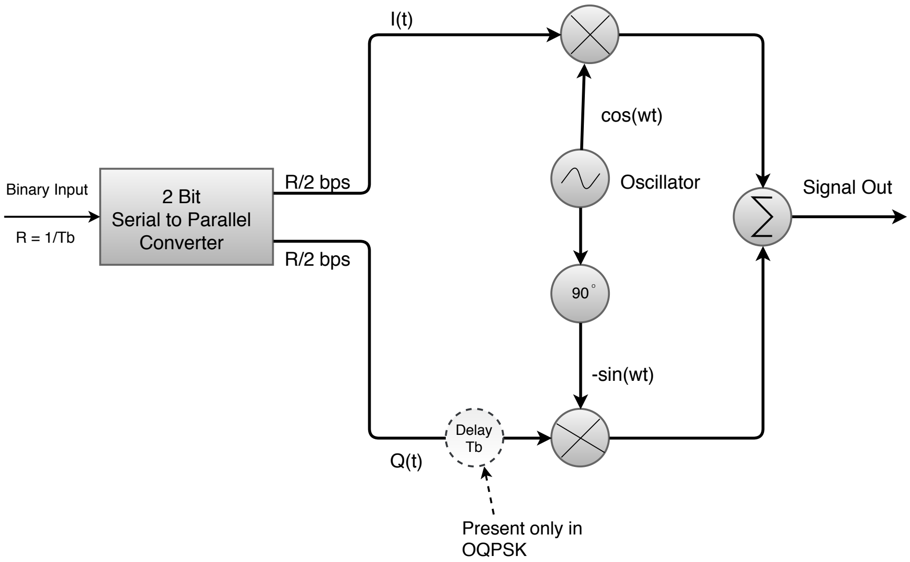

Fig. 5.2: QPSK modulation Block Diagram [11].

5.1.1 Binary Phase Shift Keying

This is the most straight forward type of PSK. Binary here refers to the use of two phase offsets, one for logic high and the other for logic low. There is 360° to work with, so the maximum differences between the phase offsets is 180°. As shifting a sinusoid by 180° is the same as inverting it, BPSK can be thought of as inverting the carrier in response to one logic state and leaving it alone in response to the other logic state [36]

5.1.2 Quadrature Phase Shift Keying

BPSK transfers one bit per symbol. QPSK is a modulation scheme that allows one symbol to transfer two bits of data. There is need for four phase offsets to accommodate the four possible two-bit numbers (00, 01, 10, 11). For maximum separation, separation between the phases is 90°.

The advantage of QPSK over BPSK is higher bitrate. If the same symbol period is maintained, the rate at which data is moved from the transmitter to the receiver is doubled. The downside is system complexity [36]. Fig. 5.2 shows the QPSK modulation block diagram. It shows that QPSK modulator maps 2 bits per symbol [11].

As shown, input binary datais divided into two streams uisinf S?P converter. One stream is known as the in-phase (I) and the other is lnown as quadrature phase (Q). LO (Local Oscillator) generates $cos(\omega t)$ which represents the I signal and a $90\,^{\circ}$

phase shift gives $\sin(\omega t)$ which represents the Q signal. Both I and Q are combined to produce the QPSK signal as shown in Fig. 5.2.

The following mathematical equations are useful in understanding QPSK modulation technique:

- **I signal**
  $\cos(\omega t)$, binary 1,
  $-\cos(\omega t)$, binary 0.
- **Q signal**
  $\sin(\omega t)$, binary 1,
  $-\sin(\omega t)$, binary 0.

where ω is the angular velocity which equals to $2\pi f$ where f is the frequency [11].

5.1.3 Dual Polarization Quadrature Phase Shift Keying

Dual Polarization Quadrature Phase Shift Keying (DP QPSK) is used in optical communication to represent laser output into symbols for transmission in order to reduce the bandwidth in the transmission of information. For example, in order to transmit 100 Gbps only 25 Gsymbols per second is required because DP-QPSK represents 4 bits per symbol [11]. Fig. 5.3 and Fig. 5.4 shows the QPSK modulation block diagrams for transmitter and receiver respectively.

5.2 AMPLITUDE SHIFT KEYING

Amplitude-Shift-Keying (ASK) also known as "On-Off"-Keying (OOK) is a technique used in modulating the intensity of carrier signal as shown in figure 5.5.The simplest form of OOK is achieved by switching the source between on and off states. The message signal is modulated onto optical carrier of high frequency[13]. The extinction ratio (ER) is the characteristic in ASK modulation that defines the relation between the signal levels in on and off state. Typical ER values vary between 8-12 dB depending on the signal bitrate [37] A carrier frequency signal is imposed onto the message signal thus. For a binary signal, binary 1 is transmitted with A watts and binary 0 is transmitted with 0 watts [13].

Multilevel signaling can be achieved in advanced optical communication systems, where more than one bit per symbol is transferred. Here two level binary signals are transmitted instead of one. This increases the transmission capacity according to the equation $M = 2^N$ where M is the signal level and N is the number of bits per second. This is called M-ary signaling. $M = 4$ is mostly used and it results in double transmission capacity (4-ary ASK) [13]. To triple the transmission capacity,

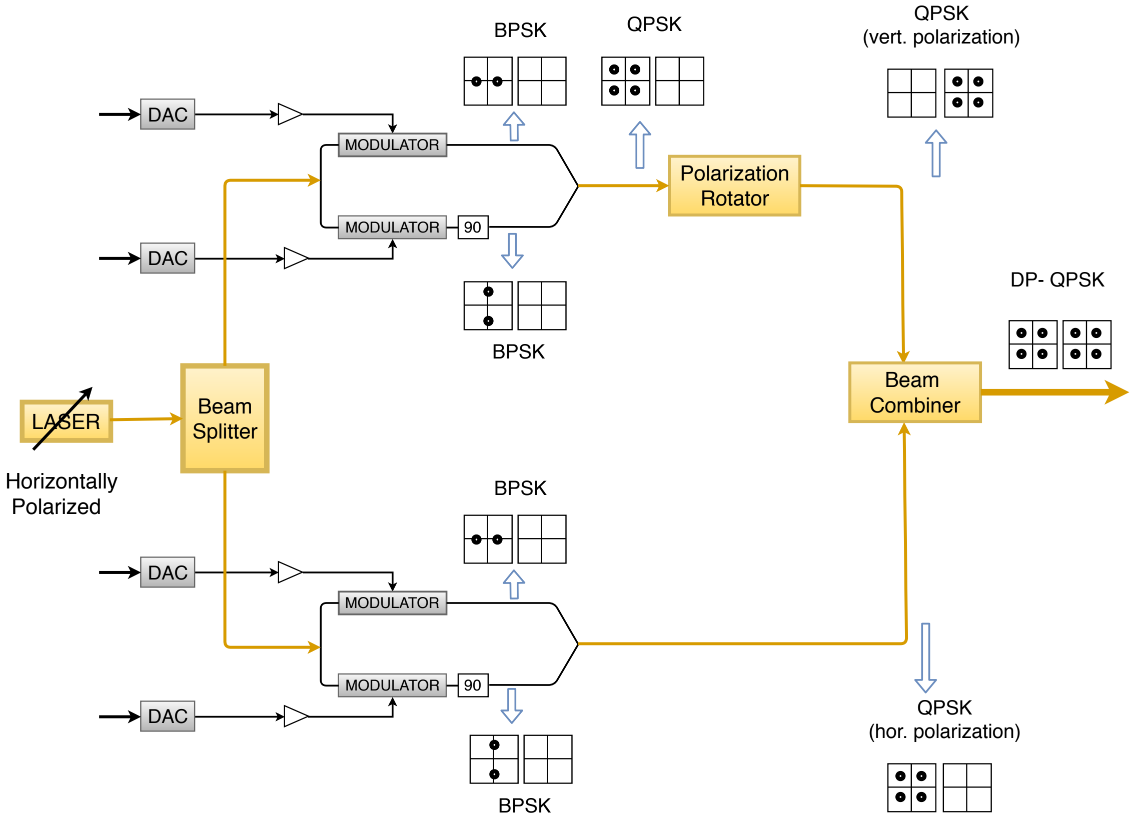

Fig. 5.3: A schematic shows a dual-polarization (DP) in phase/quadrature (I-Q) optical transmitter demonstrating the evolution of the DP quadrature phase-shift keying (DP-QPSK) signal constellation. The electronic digital-to-analog converters (DACs) are needed for higher-level modulation formats, such as DP-16QAM. Note: This transmitter is required for each optical channel in a WDM system [11] [12].

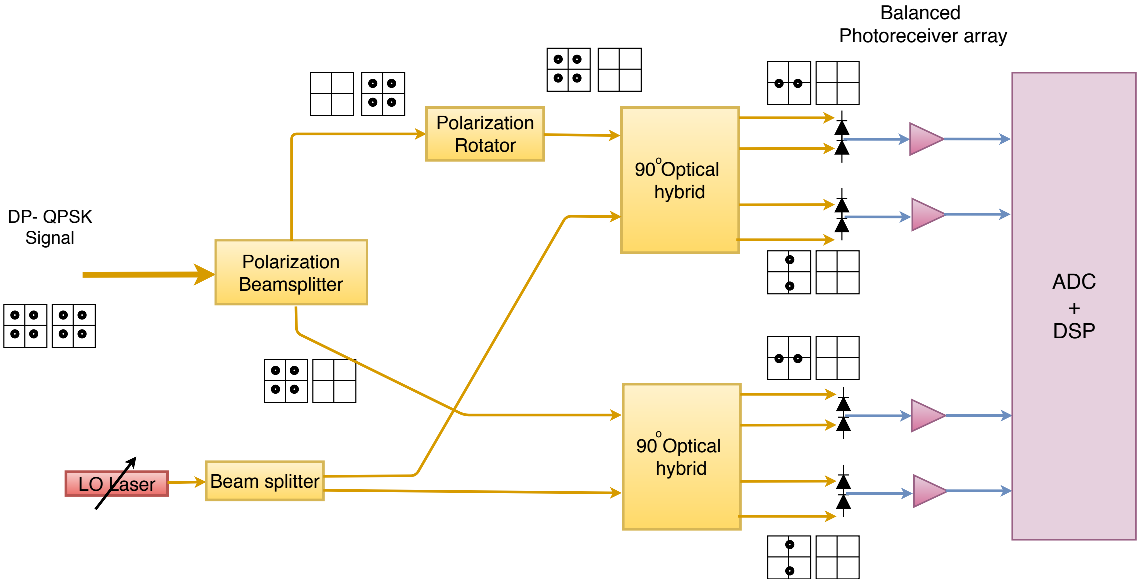

Fig. 5.4: A schematic of a coherent dual-polarization I-Q optical receiver shows the deconstruction of the DP-QPSK signal constellation. Mismatch in optical phase and polarization between the LO laser and the received signal have been ignored in the signal constellations. Note: This receiver is required for each optical channel in a WDM system [12].

an 8-ary ASK has been reported but as channel capacity improved by using 8-ary ASK, the OSNR and receiver sensitivity is degraded [13].

5.3 FREQUENCY SHIFT KEYING

Frequency-shift keying is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier signal. In FSK, the signal transmitted for binary ones and binary zeros (marks and spaces respectively) are [14]

$$s_1(t) = A\cos(\omega_1 t + \theta_c),\ 0 < t \leq T \tag{5.1}$$

$$s_2(t) = A\cos(\omega_2 t + \theta_c), 0 < t \leq T \tag{5.2}$$

respectively and it is called a **discontinuous phase** FSK system, this is because at switching times, the phase of the original is discontinued.

Fig. 5.6 shows the generation of the above signal.

The resultant modulated signal representing the binary signal is shown in Fig. 5.7.

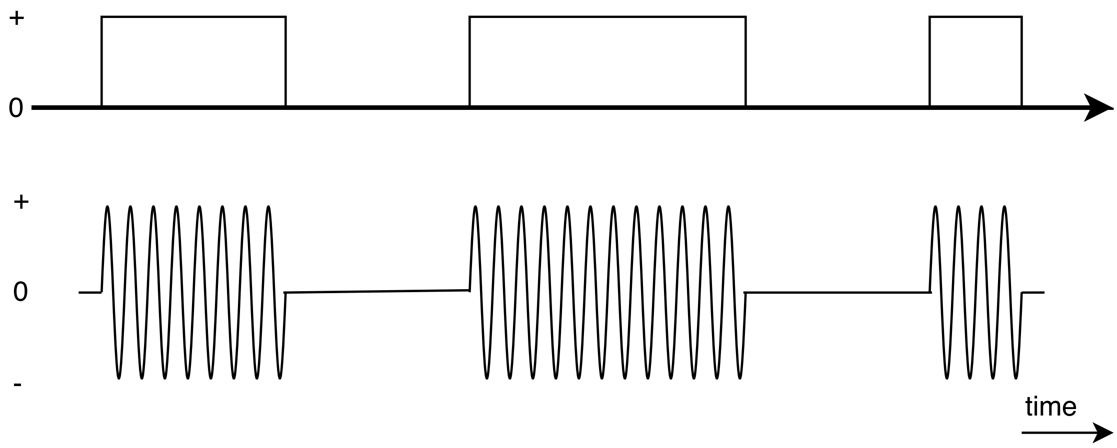

Fig. 5.5: ASK modulation format, upper: binary signal, lower: ASK modulating signal [13].

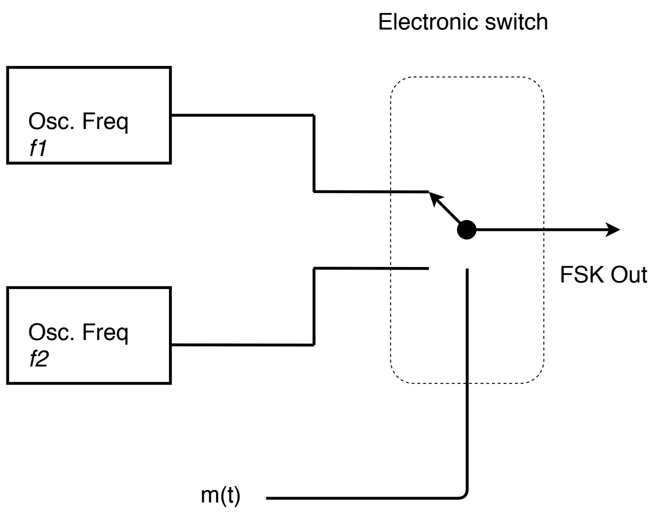

Fig. 5.6: Frequency-shift Keying generator [14].

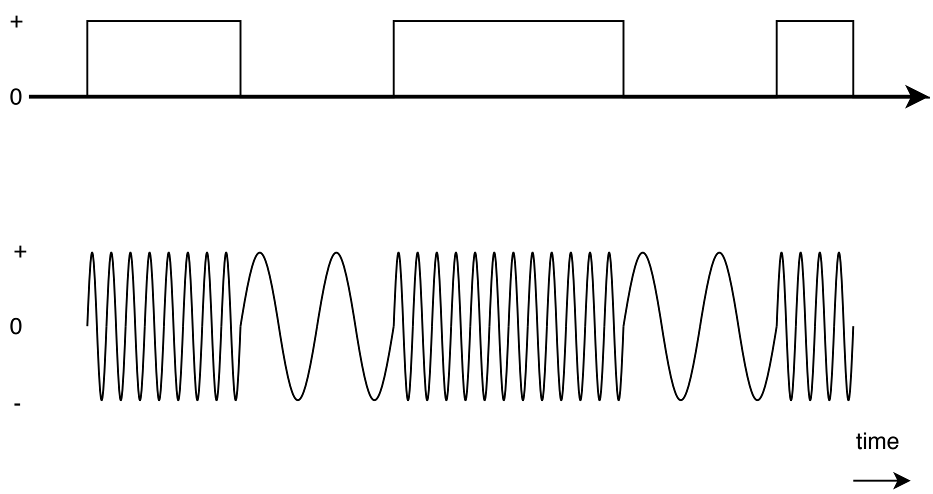

Fig. 5.7: FSK modulation format, upper: binary signal, lower: FSK modulating signal[13].

The bit intervals and the phase of the signal are usually determined by use of a phase-lock loop. If this is done, then the signal can be decoded by the two separate matched filters.

The output of one of the one of the matched filters will be $+E$ and the other zero under the assumption that the signals are mutually orthogonal (E is the energy of the signal). To achieve the decoding of the **bandpass** signal therefore, the outputs of the two filters are subtracted and the results are compared to a threshold.

6 DESIGN AND SIMULATION OF DATA TRANSMISSION

In this thesis, simulation of transmission of a 100 Gbps system is performed using PHOTOSS photonic system simulation software. This is achieved using dual-polarization quadrature shift keying, DP-QPSK modulation format (Sec. 5.1.3). For the block diagram of the transmitter and the receiver refer to Section 5.1.3. In this chapter, the simulation setup and the parameters are described. The results of the simulation are explored and then comparison to the current trends in the above 100 Gbps transmissions is done.

6.1 PHOTOSS Simulation software

PHOTOSS is a standalone package for simulation of photonic transmission systems. It does not depend on an underlying simulation framework [38].

Graphical design and analysis of optical systems are performed using the user interface. Its performed by placing and connecting components on the grid. It contains extensible components of different complexities which are represented by models. User specific components can also be added using the included programming interface [38].

The main purpose of the PHOTOSS application is to carry out numerical simulations of optical/pho-tonic transmission systems. Generally, a simulation of these systems incorporates the interplay between underlying PHOTOSS concepts to produce an accurate emulation of the real, physical system [38]. In the following section, the individual components of the simulation and the concepts behind them will be briefly described. For further studies and understanding of the concepts of PHOTOSS software, please reference to [38].

6.2 Design

As already mentioned above, the design and implementation of the simulation is performed in the PHOTOSS photonic simulation software.

The simulation scheme is set up as shown in Fig. 6.1. It consists mainly of three parts: the transmitter, the transport, and the receiver. The properties and parameters of the components used in the simulation are briefly described.

1. **The Transmitter**: The transmitter is split into two polarizations namely: the X-polarization and the Y-polarizations. Both of these polarizations are

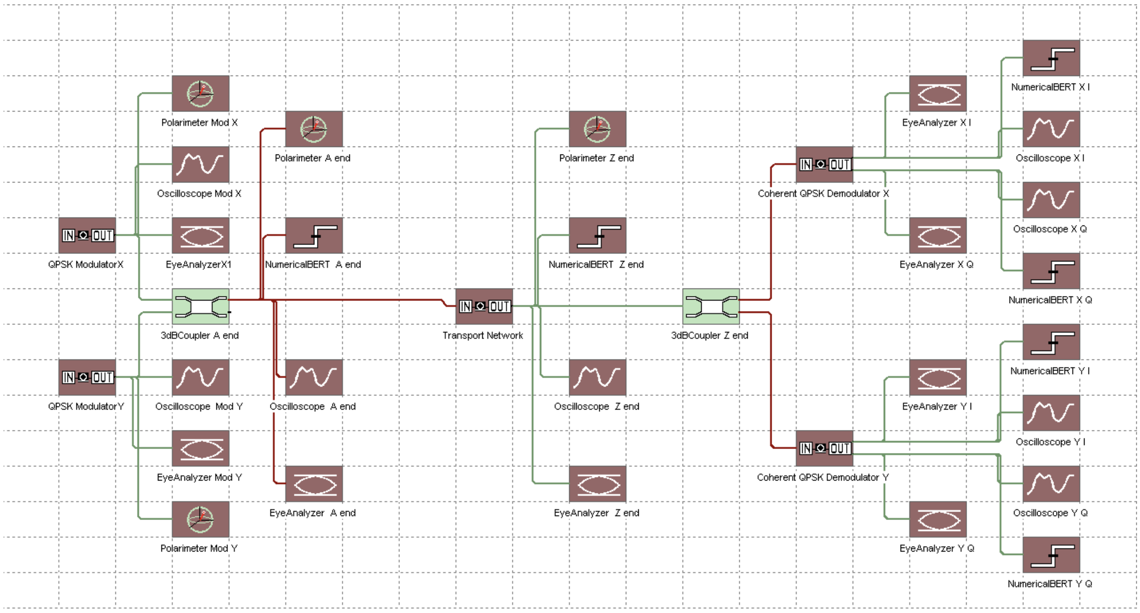

Fig. 6.1: Scheme of simulation in PHOTOSS

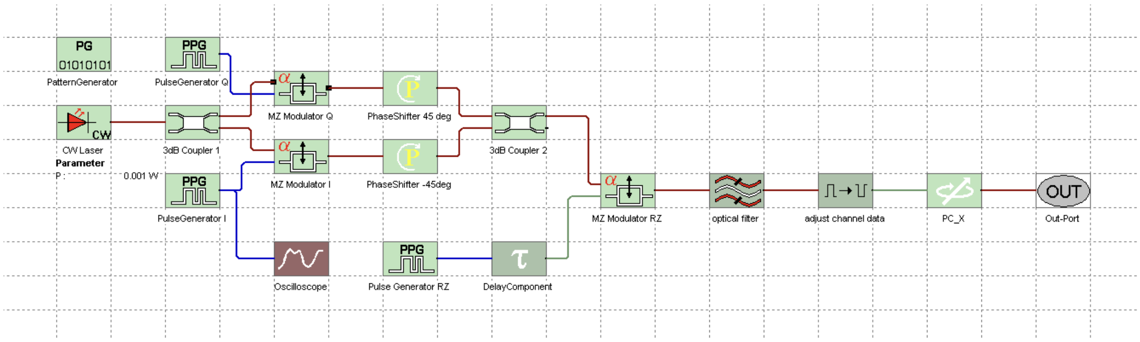

Fig. 6.2: Scheme of the X-polarized transmitter

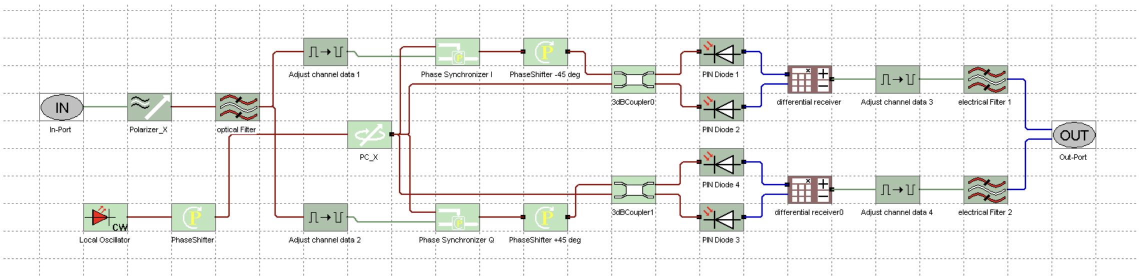

Fig. 6.3: Scheme of the X-polarized receiver

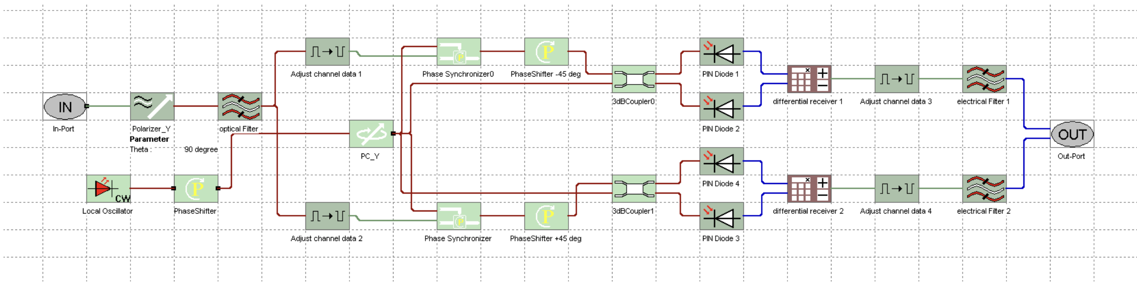

Fig. 6.4: Scheme of the Y-polarized receiver

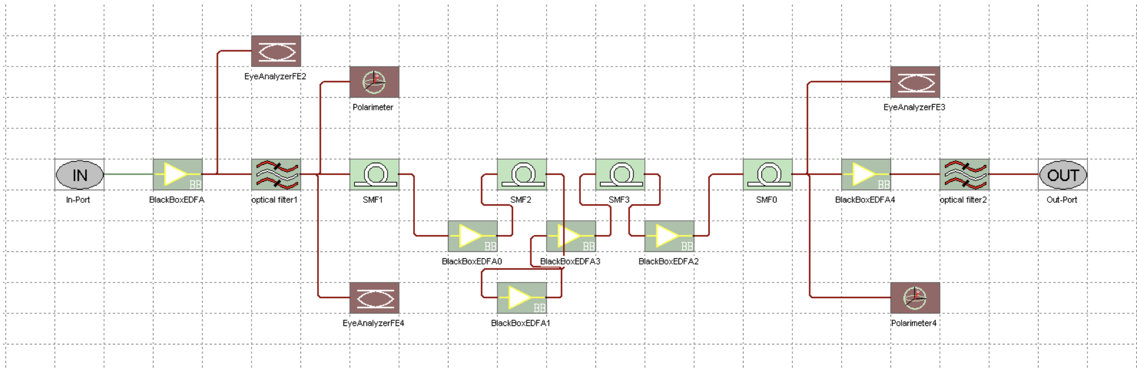

Fig. 6.5: Scheme of the transport

similar in design, except the parameters of the *polarization Controller* (see Fig. 6.13 for the parameters) which are set to correspond to the x-plane and y-plane for the respective polarization states. Fig. 6.2 shows the x-polarized transmitter.

Each transmission *Network*[1] functions as an independent DQPSK transmitter. It is composed of a continues wave (CW) laser (Fig. 6.8 for parameters used) which provides light input to the system. Using a 3 dB coupler, the light is split into two *MZ-Modulators* (Fig. 6.11 for parameters used) for the I and the Q bits.

A *Pattern Generator* creates random pseudo-random bit sequence (PRBS) bits. The parameter "BitRate" of the *Pattern Generator* actually corresponds to a baud rate when considering higher order modulation formats [38]. For a reference bit rate of 100 Gbps as is used in the this simulation, the bit rate of the Pattern Generator (i.e., the baud rate) is set to half of that value since two bits are transmitted per QPSK symbol. The rest of the parameters used in the pattern generator are shown in Fig. 6.12.

The function of the MZ Modulator is to modulates the light from the CW

[1] The *Network* and the *Iterator* contain further components in a nested sub-structure within them

laser using the bit pattern from the Pulse Generator (the which obtains the differentiated bit patterns from the Pattern Generator). This occurs for both Q and I bits. The parameters of the Pulse Generator are as shown in Fig. 6.14.

The bits are phase shifted by 90° using the PhaseShifters. In practice, only the Q bits are shifted by an entire quadrature (90° or $\frac{\pi}{4}$ rads, hence the *Q* in Q bits). In this simulation, however, the same goal is achieved by shifting both the Q and I bits by 45° and −45° respectively. Both bit patterns are then combined using a 3 dB coupler and sent into another modulator connected to a return-to-zero (RZ) pulse generator with a delay component. Parameters shown in Fig. 6.11 and 6.9.

Here, the modulated bits are then passed through an optical filter, the channel data is adjusted and finally passed through a Polarization Controller. The Polarization Controller sets the required polarization of the light from each modulator to vertical or horizontal polarization.

2. **The Transport**: The transport mainly contains the optical channel and the necessary components needed to compensate for power losses and optical dispersions.

   After the light from the X and the Y QPSK modulators has been manipulated, it is converged into a 3 dB coupler and sent into the transport network. The network in this simulation consists of Erbium-Doped Fiber Amplifier (EDFA) amplifiers, optical filters and the optical channel which is a single mode optical fiber. The parameters of the optical fiber are shown in Fig. 6.15.

   First, the signal is amplified and filtered before it is launched into the fiber. There are a total of 4 fiber connections in this simulation. The light signal is amplified at the end of each fiber before it is launched into the next fiber. To minimize dispersion, each fiber is followed by dispersion compensation fibers which mirrors the dispersion characteristics of the previous one.

   At the end of the channel, the signal is filtered and split by a 3 dB coupler into respective demodulators for X and Y polarized coherent receivers.

3. **Coherent QPSK Demodulators**: The signal enters this Network and is passed through a polarizer then through an optical filter. It is split into Q and I and the channel data is adjusted. The phase is synchronized and coupled with a signal from a local oscillator that has been phase shifted (by 12°) in this case, and passed through a polarization controller.

   The signals are then split and fed into PIN diodes which send the signals into a differential calculator.

   Finally the data is adjusted, filtered using an electrical filter and passed into

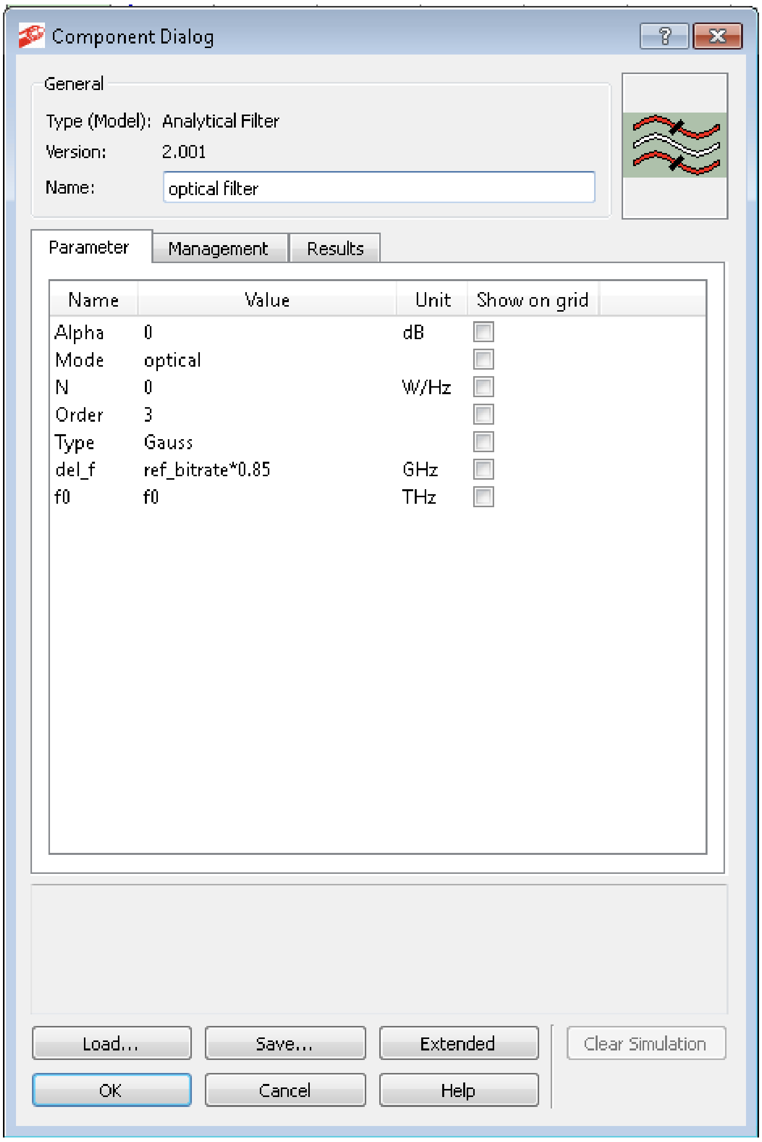

Fig. 6.6: Parameters of the Analytical Filter used.

the receiving devices (a network component i.e., a router or switch).

6.3 Simulation parameters

This section shows the simulation parameters for the components used in the simulation to provide figures of references.

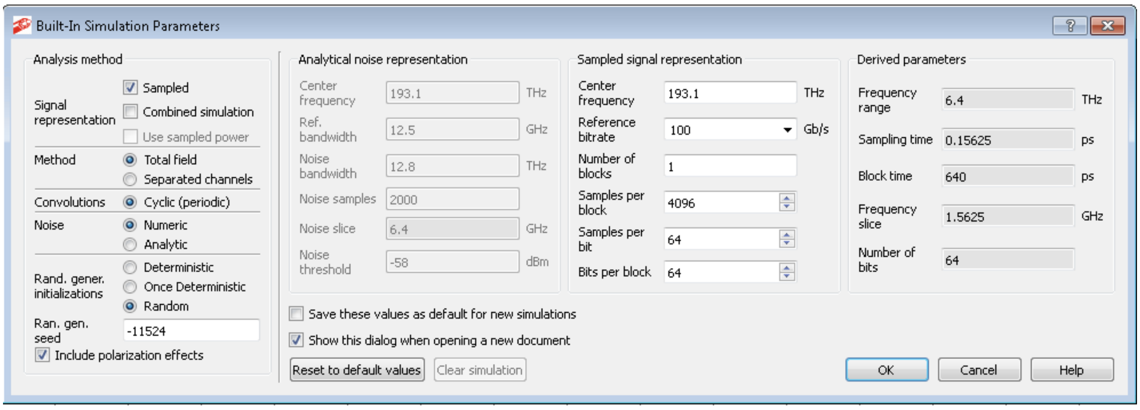

Fig. 6.7: Parameters used in Built-in Parameters.

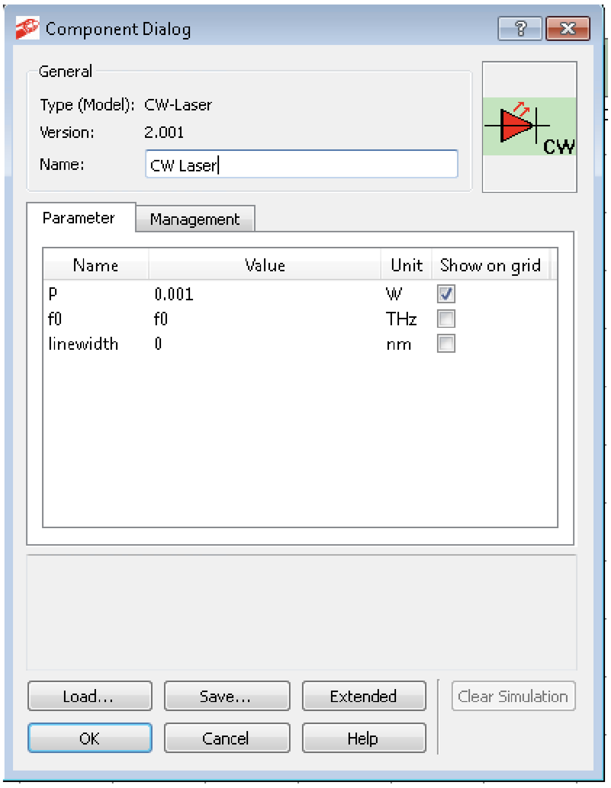

Fig. 6.8: Parameters for the continuous wave lasers.

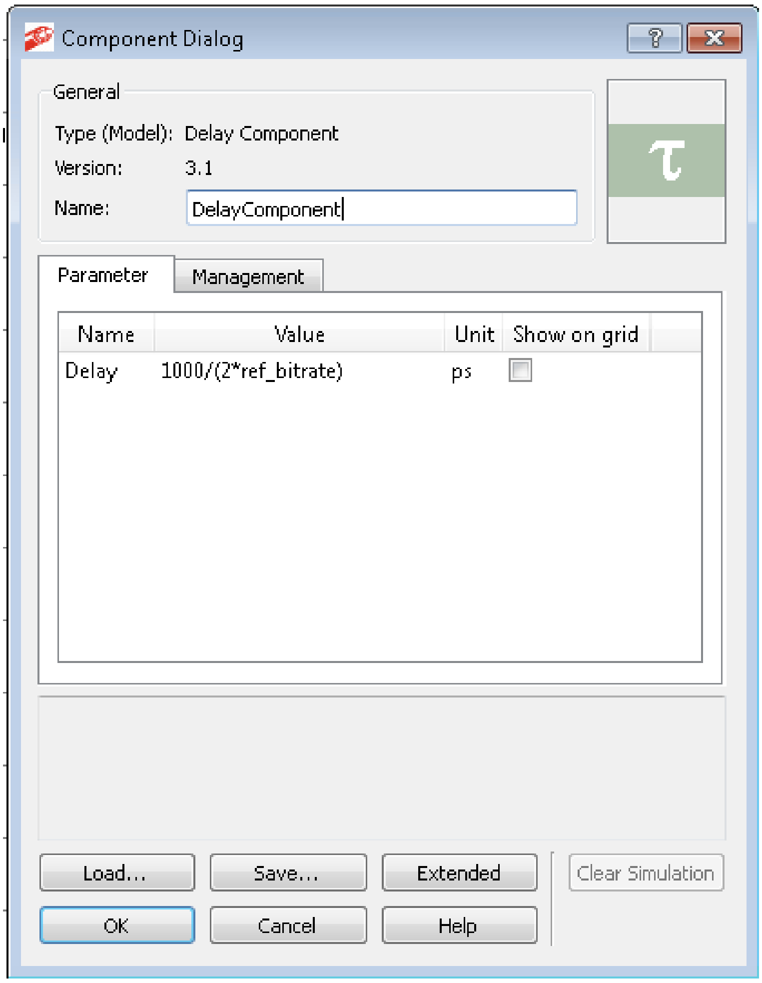

Fig. 6.9: Parameters of the Delay Component

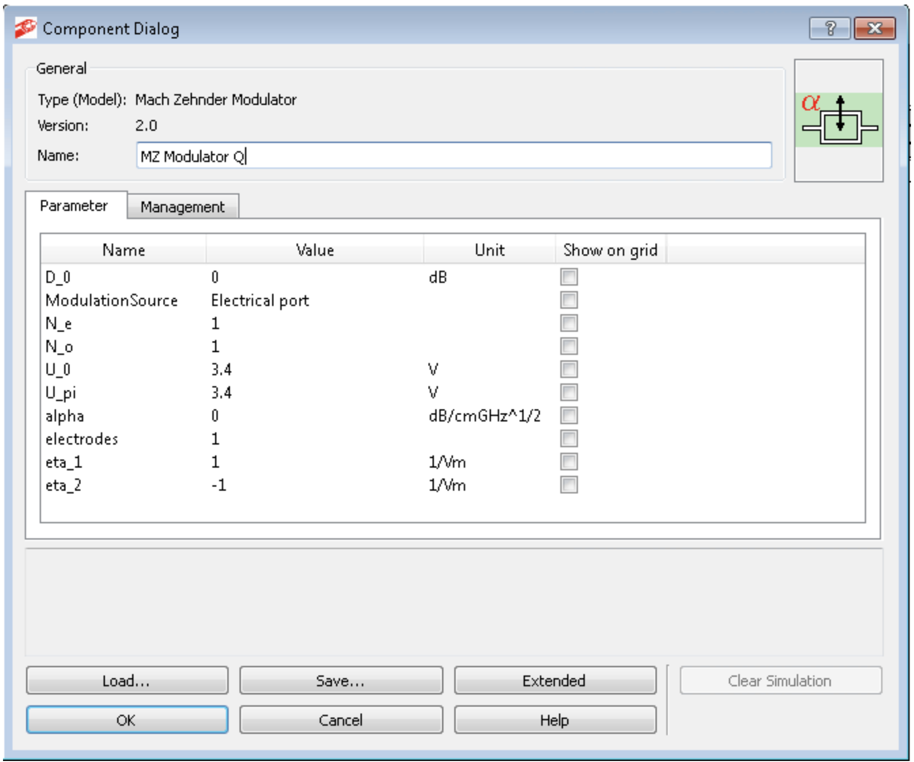

Fig. 6.10: Parameters of the MZ Modulators.

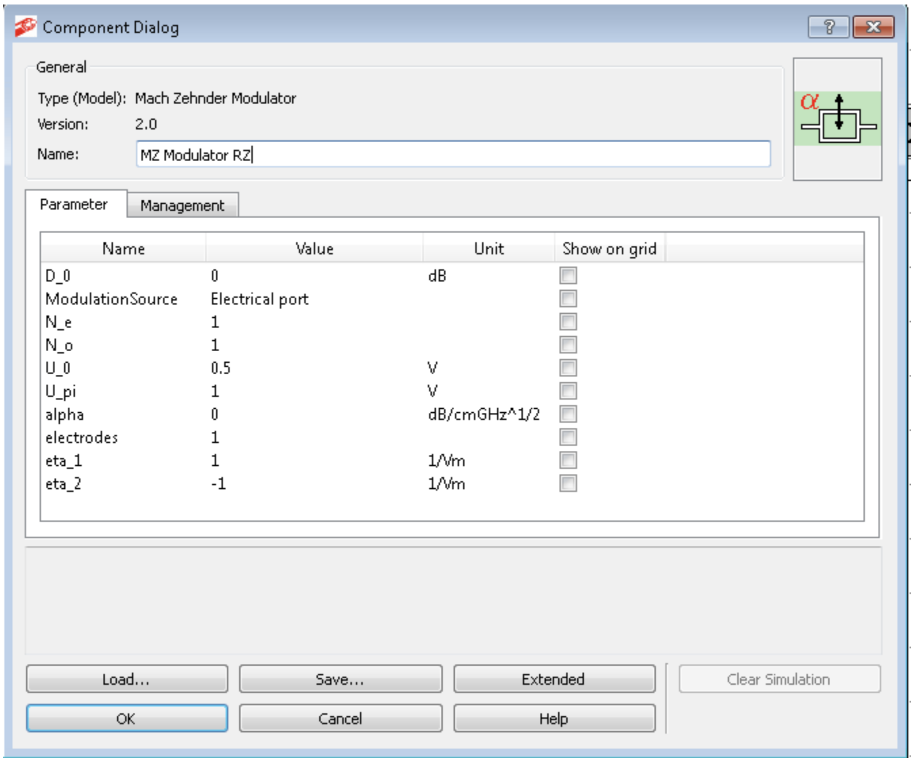

Fig. 6.11: Parameters of the MZ Modulator return-to-zero.

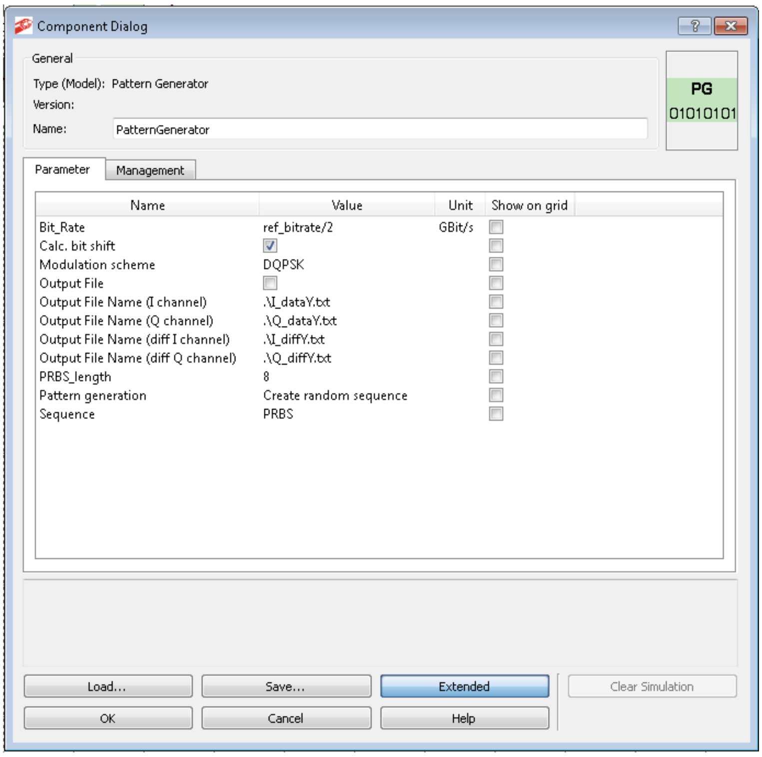

Fig. 6.12: Parameters of the Pattern Generator.

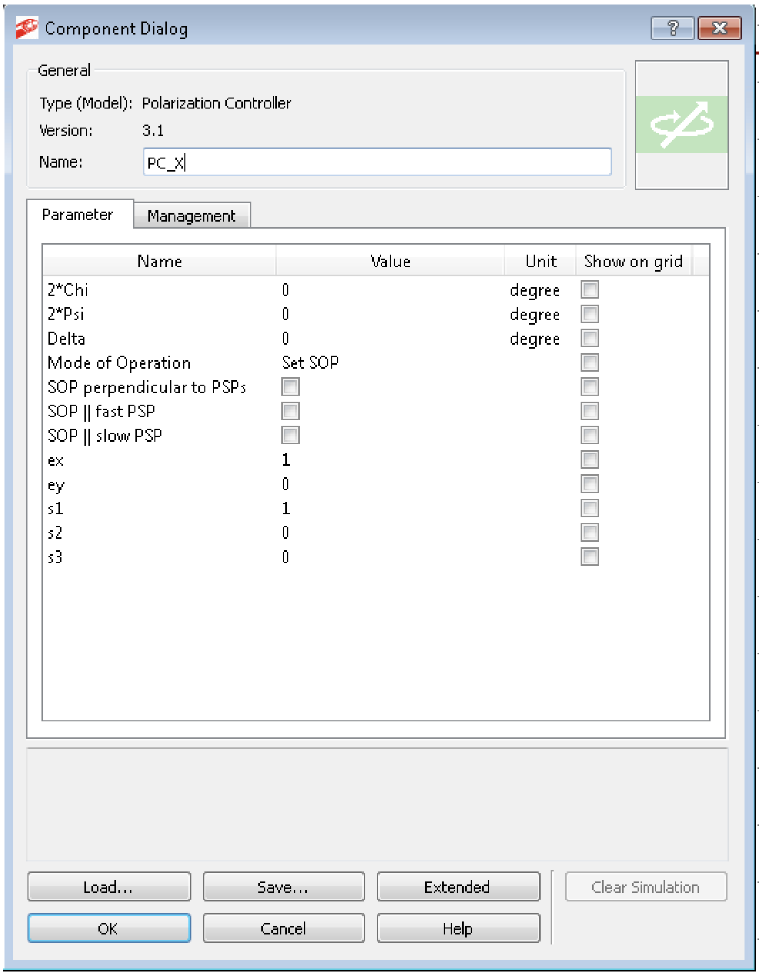

Fig. 6.13: Parameters of the Polarization Controller.

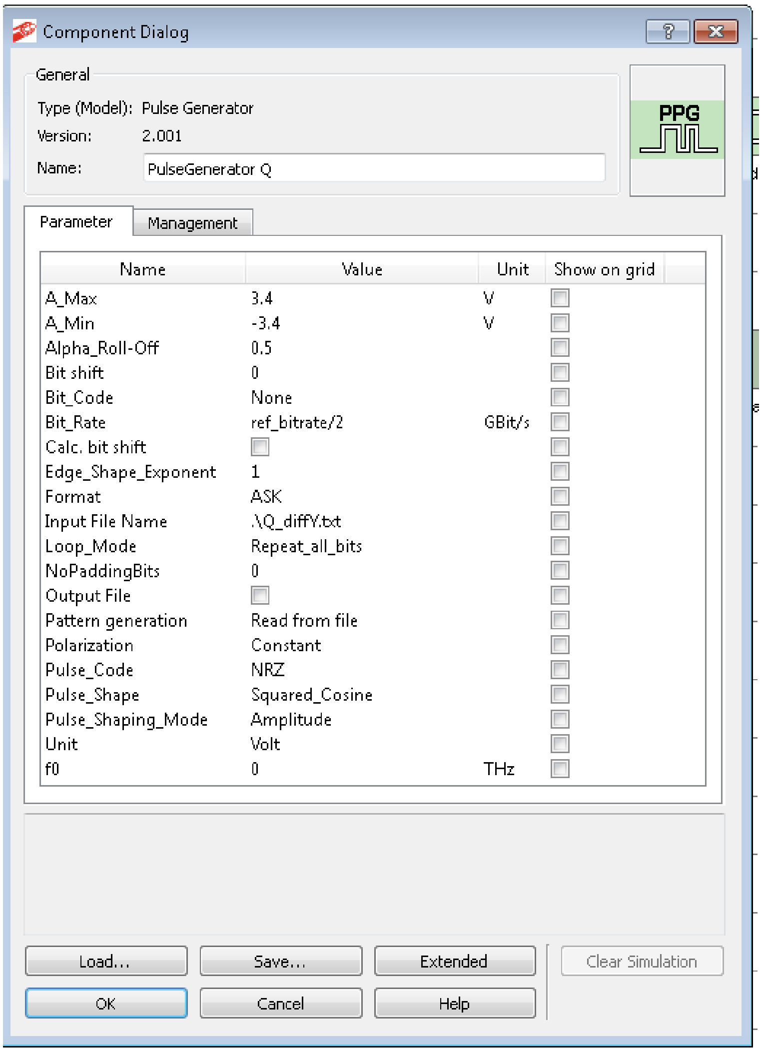

Fig. 6.14: Parameters of the Pulse Generator.

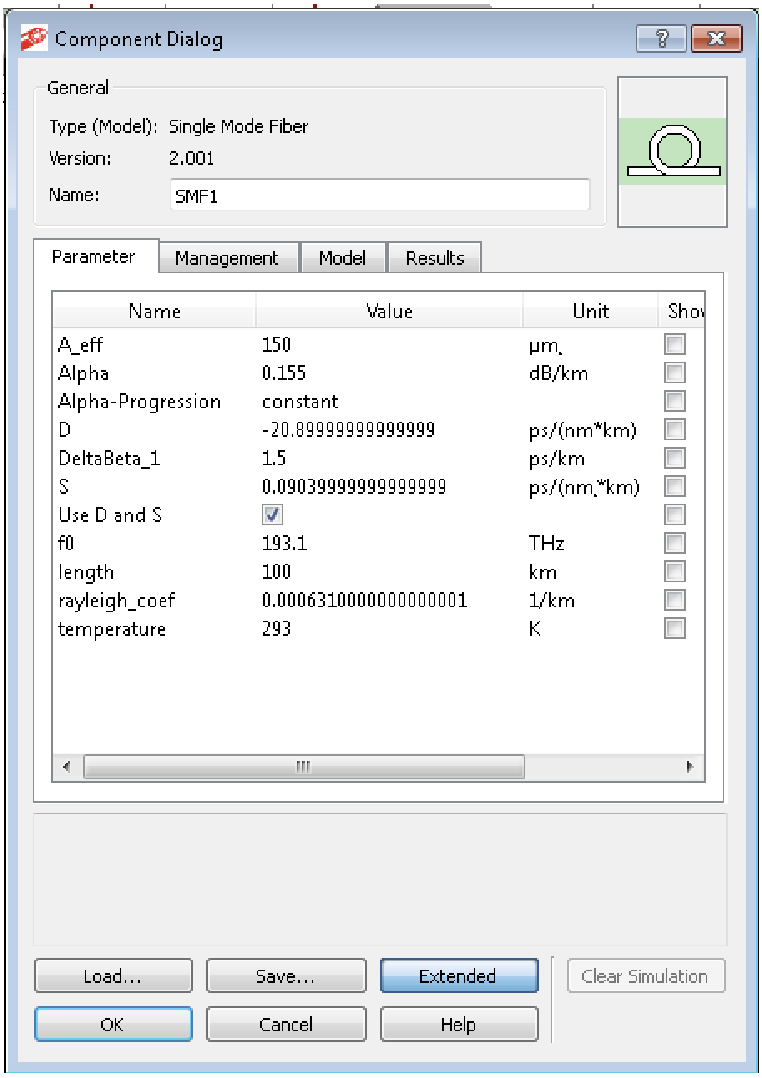

Fig. 6.15: Parameters of the Optical Fibers used. Note: compensation fiber has a mirror dispersion coefficient, D.

7 SIMULATION AND RESULTS

This chapter contains graphical representation of the results obtained in the simulation. Discussions and comparisons follow in the subsequent section.

7.1 Results and Comparison to expected values

Fig. 7.1 shows the constellation of the signal when it exits the modulator. In the figure, it shows how the bits have been spread out at an angle of 90 from each other. which agrees with expectations.

7.1.1 Constellations

In comparison to the constellation at Z-end (receiver/demodulator end) shown in Fig. 7.2, it is clear that the signal has been distorted, nevertheless, the bits can still be distinguished. this is also expected as the signal gets distorted as it travels in the fiber.

One of the main causes of signal distortion is chromatic dispersion. In the simulation, chromatic dispersion was reduced by using fibers with negative dispersion coefficient to try to restore the original signal after passing through one of the optical fibers with positive coefficients.

In the scheme of the transport Network (Fig. 6.5), there four fiber segments in total. The first one has a positive coefficient (as shown in the parameters in Fig. 6.15). Once the signal power has been amplified and the noise filtered (using the EDFA amplifier and the analytical filter respectively), the signal launches into the second fiber whose dispersion coefficient mirrors the first one. This process is repeated in the second pair of fibers.

Each fiber has a length of 100 m. Together, the total distance achieved in the simulation is 400 m. In real life and in some experiments carried out, longer distances in the range from 6,000 km up to 12,000 km have been achieved using similar fiber parameters [39]. This suggest that there is still room for improvement and it is possible to obtain better results than in this simulation.

Fig. 7.7 shows the constellation on the I channel of the x polarization. It is not necessary to attach the constellations of the remaining channels since they are very similar. Since this is one polarization of the DP QPSK, it is basically one channel of QPSK signal constellation, i.e. a BPSK constellation. This corresponds to the expectations.

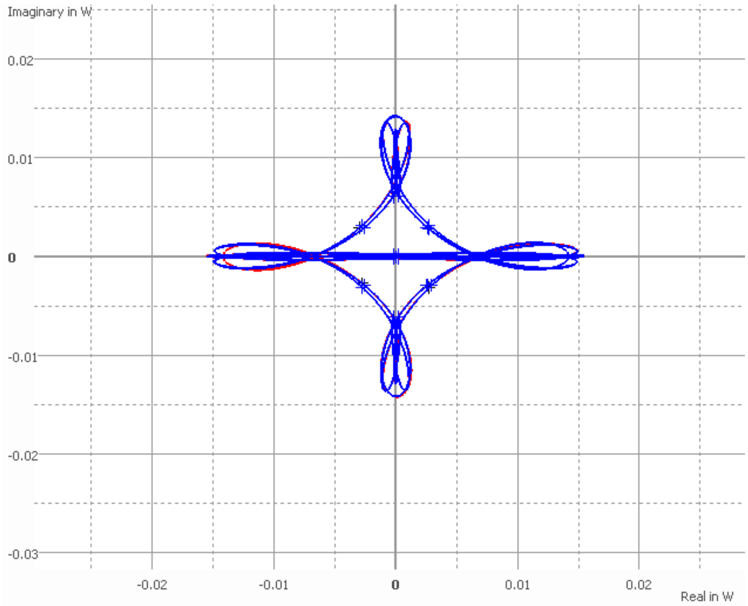

Fig. 7.1: Constellation at the transmitter side before launching into the fiber.

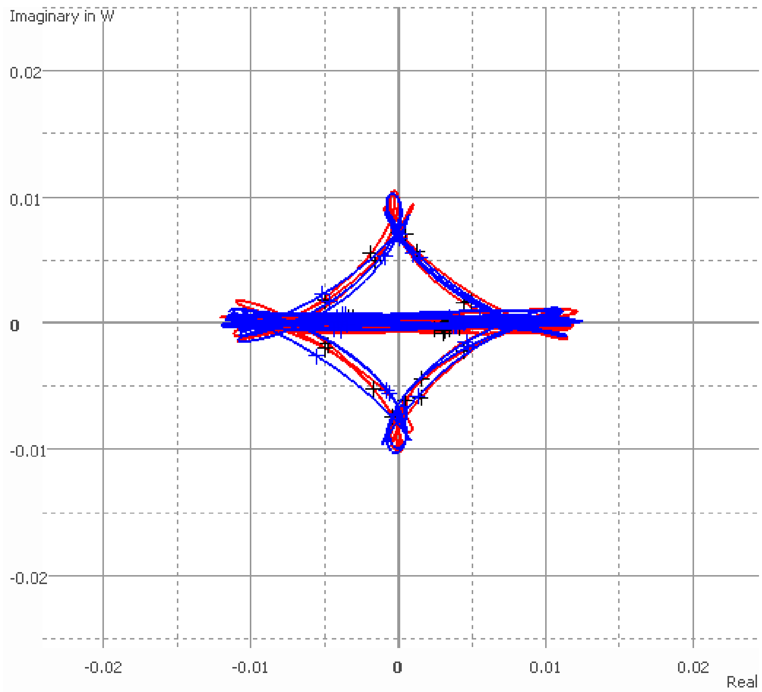

Fig. 7.2: Constellation of light as it emerges from the transport and is launched into the coherent QPSK demodulator.

7.1.2 EyeAnalyzer

Similarly as the constellation diagrams show degradation of the signal as it propagates through the fiber, same results can be observed using the EyeAnalyzer.

Fig. 7.3 shows the results of the EyeAnalyzer at the transmission end of the fiber. Comparing with the results at the receiver end (Fig. 7.4), it is visible that the signal has spread out more. Fig. 7.5 and Fig. 7.6 show the signal at the transmitter and receiver end of the fiber.

Fig. 7.8 shows the eye pattern of the Q bits of the x polarization. Similar results are observed in the rest of the bits on both polarizations. It is clearly visible that the eye is open and that the signal was correctly transmitted o the receiver end. With this eye, bits can be read off with minimal errors.

7.2 Possible Improvements

As already mentioned above, this system could be optimized to transfer the same amount of data over longer distances in the range of thousands of kilometers.

- **Graded index**: This is an optical fiber whose refractive index decreases with increasing radial distance. This reduces modal dispersion.
- **Dispersion compensation**: Dispersion-shifted fibers (as well as negative dispersion fibers) have been developed to control dispersion just as graded index fibers were developed to reduce modal dispersion. Using this method, dispersion can be minimized in and a single fiber can span longer without needing regeneration [40].
- **Fiber Intrinsic Loss**: This originates from Rayleigh scattering radiation caused by irregularities in fiber structure and absorption by impurities
- **Degradation of beam quality**: is a critical factor for future power scaling of fiber optical lasers and amplifiers [41]. It has been demonstrated that an all solid fiber with chirally-coupled cores (CCC) increases the core diameter up to 33.3 μm and have effective SM [41].

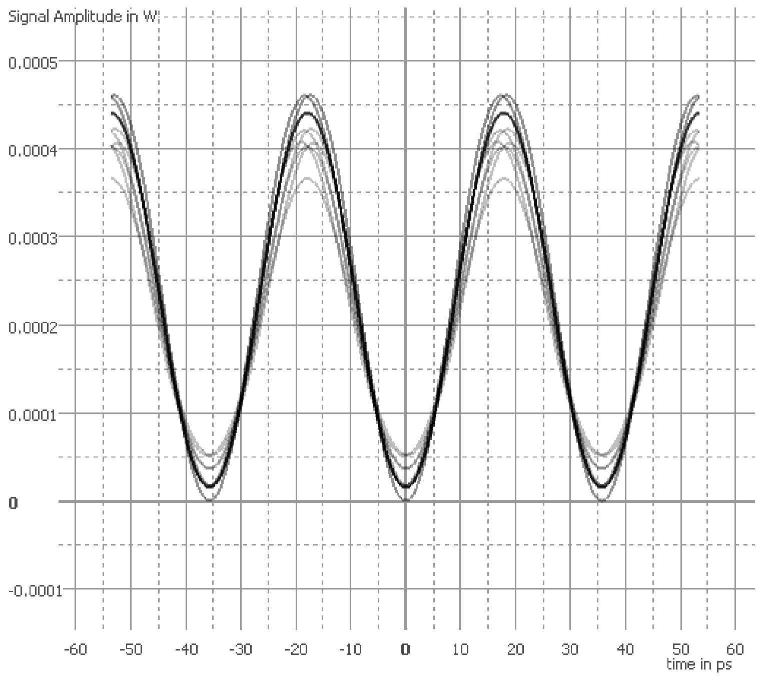

Fig. 7.3: Results of the EyeAnalyzer at the transmission end after modulators.

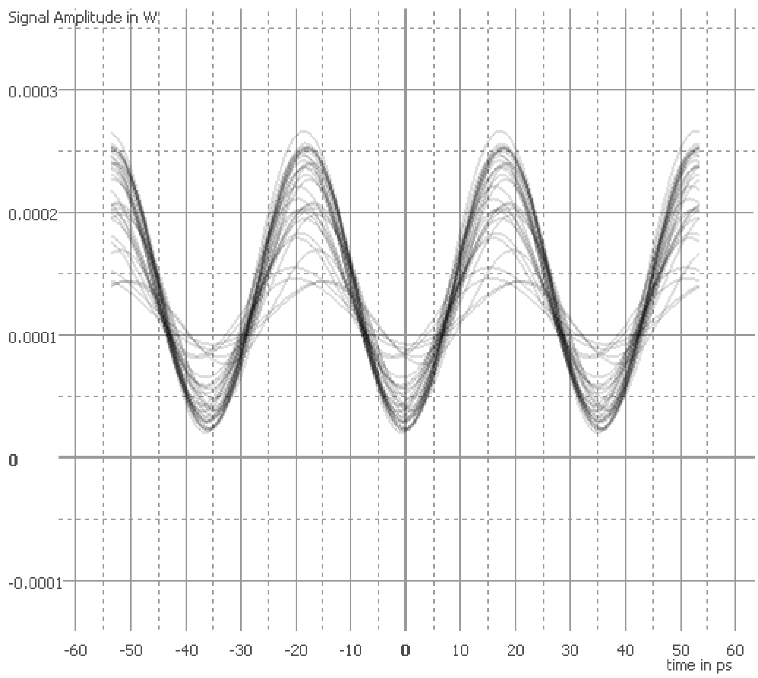

Fig. 7.4: Results of the EyeAnalyzer at the receiver end before demodulators.

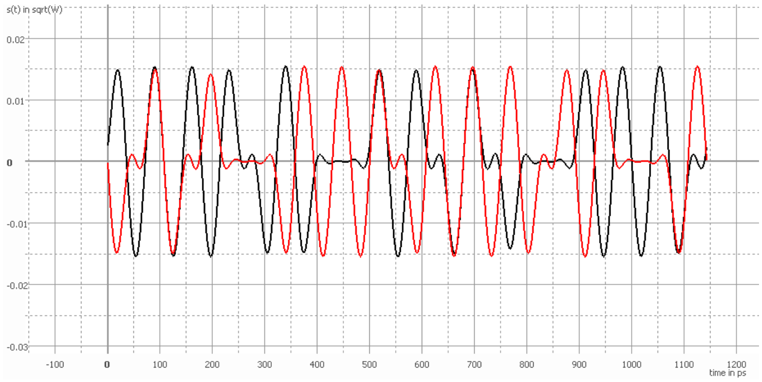

Fig. 7.5: Oscilloscope output at the transmission end after demodulators.

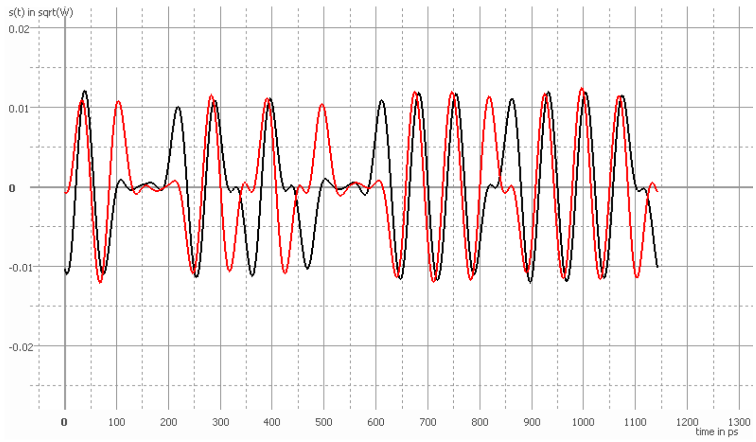

Fig. 7.6: Oscilloscope output at the receiver end before demodulators.

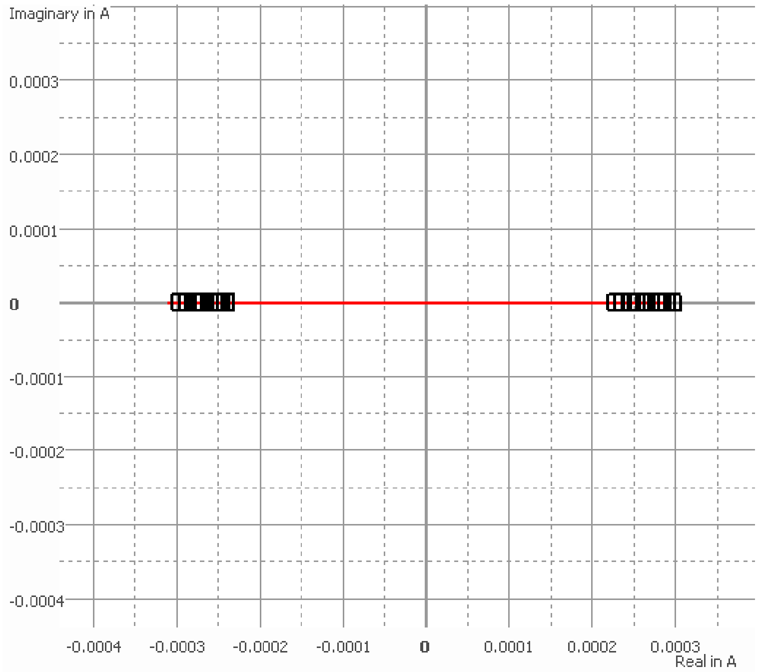

Fig. 7.7: Constellation on the I channel of the x polarization. Similar constellations are observed in the rest of the other channels.

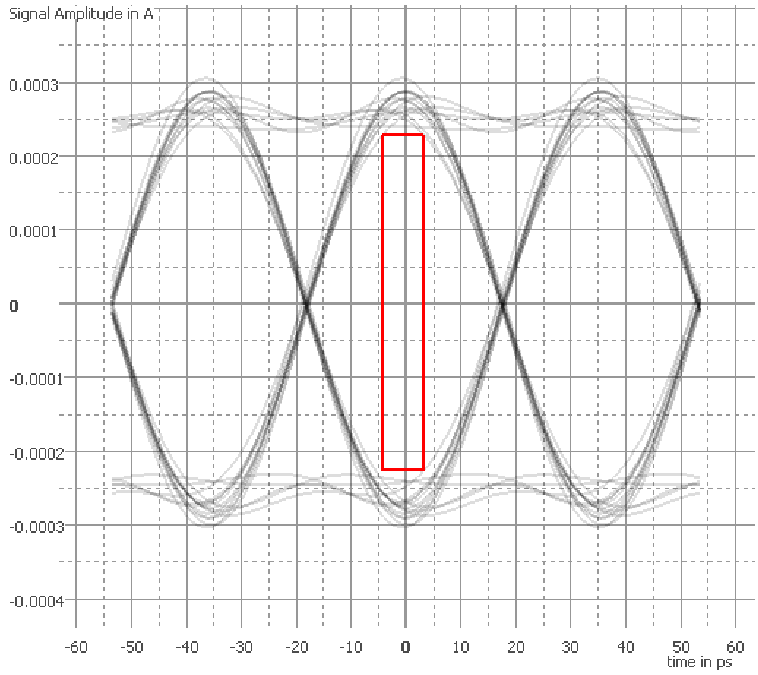

Fig. 7.8: Eye pattern of the Q bits of the x polarization. Similar results are obtained from the rest of the channels in the X and the Y polarizations.

8 Conclusion

The thesis is focused on optical fiber transmission. The different modulation methods used to transfer data in telecommunication. Problems associated with fiber transmission and in fact most of them apply to any other form of signal transmission. Nonetheless, some such as dispersion are unique to optical fiber transmission.

The theoretical part briefly describes the properties of light with models (ray model and wave model). It then goes on to describe optical transceivers and polarizations. Comparisons are made between fiber and copper wires. The optical fiber is described. Different types of optical fibers are outlined and briefly described, including ITU recommendations.

Further on, signal loss in optical fibers is discussed. Different modulation formats and upcoming technologies that use light to transfer information are discussed among which are quantum key distribution, QKD and optical HDMI. A more detailed description is put on dual polarization quadrature phase shift keying, DP QPSK, as it is implemented later in the practical part.

The practical part consists of a simulation of a 100 Gbps transmission using DP QPSK using PHOTOSS simulator. During the simulation, positive results are observed and the output agrees with expectations. A minor setback was that the span of the fiber does not correspond to other experiments and implementations. The reason for this could be that the system needs further optimizations to improve transmission quality.

In conclusion, this thesis briefly points out a small section of a very wide topic. Fiber optic communication is very crucial in the development of the communication sector especially for the 4^{th} industrial revolution. The world will be more connected and fiber optics play one of the biggest role in interconnecting the world. More so, there is an increase in demand of bandwidth per user.

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List of symbols, physical constants and abbreviations

OAM	Orbital Angular Momentum
MIMO	Multiple Input Multiple Output
SNR	Signal to Noise Ratio
WDM	Wavelength Division Multiplexing
PLCs	Planar Lightwave Circuits
PICs	Photonic Integrated Circuits
LED	Light Emitting Diodes
MM	Multi-Mode (fibers)
SM	Single-Mode (fibers)
FMF	Few Mode (fibers)
LA-PSCF	Large-Aeff Pure-Silica Core Fiber
NA	Numerical Aperture
MIMO	Multi Input Multi Output
OSNR	Optical Signal to Noise Ratio
MCF	Multi-Core Fiber
ITU-T	ITU Telecommunication Standardization Sector
ITU	International Telecommunication Union
USF	Unshifted Fiber
ZDP	Zero Dispersion Window
PMD	Polarization Mode Dispersion
LWP	Low Water Peak
DSF	Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
MFD	Mode Field Diameter
EDFA	Erbium Doped Fiber Amplifiers
NZ-DSF	Non-Zero DSF
ISI	Inter-Symbol Inteference
CWDM	Coarse Wave Division Multiplexing
GRIN	Graded Index
UV	Ultra Violet
EMI	Electromagnetic Inteference
PCM	Pulse Code Modulation
OTDR	Optical Time-Domain Reflectometer
MDP	Minimum Detectable Power
CPT	Coupled Power Theory

CMT	Coupled Mode Theory
MCC	Mode Coupling Coefficient
CME	Coupled Mode Equation
QEO	Quadratic Electro-Optical (effect)
CPM	Cross-Phase Modulation
SPM	Self-Phase Modulation
FWM	Four-Wave Mixing
SRS	Stimulated Raman-Scattering
SBS	Stimulated Brillouin-Scattering
$\mathbf{A}_{eff}$	Effective Cross-Sectional Area
QKD	Quantum Key Distribution
QKDP	Quantum key Distriution Portocols
TC	Trusted Center
NRZ	Non-Return-to-Zero
RZ	Return-to-Zero
CSRZ	Carruer-Suppressed RZ
PSK	Phase Shift Keying
BPSK	Binary Phase Shift Keying
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
Lo	Local Oscillator
DP QPSK	Dual Polarization Quadrature Phase Shift Keying
OOK	On-Off Keyin
ER	Extinction Rate
DAC	Digital Analogue Converter
FSK	Frequency SHift Keying
ASk	Amplitude Shift Keying
CW	Continius Wave (Laser)
MZ Modulator	Mach-Zehnder Modulator
CCC	Chirally-Coupled Cores

List of appendices

A Content of the CD included

The following is the content of the included disc. The version of the PHOTOSS Photonic Simulator used was

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